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ORIGINAL ARTICLE – Silviculture

Pyrene Storage Time Reduces Dormancy and Physiological Quality in *Butia Capitata* (Arecaceae) Seeds

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Abstract

This study aimed to evaluate the physiological changes in pindo palm (*Butia capitata*) seeds, a native fruit species of the Brazilian Cerrado, over time under different storage conditions. Pyrenes (endocarp + seed) were stored on the sand under shade and refrigeration conditions. The physiological quality of seeds and embryos (via *in vitro* culture) was evaluated over time. Moisture content decreased during storage until stabilization, while germination, germination speed index (GSI), and operculum resistance remained stable up to 90 days, with a significant decline at 120 and 150 days. Conversely, lipid peroxidation, measured by malondialdehyde (MDA) content, and electrical conductivity (EC) increased over time, especially after 90 days. Refrigeration promoted greater embryo elongation, but sheath and root emergence were reduced. Storage reduces seed dormancy in *B. capitata* but also decreases viability and vigor.

Keywords: Germination, longevity, deterioration, embryo culture, *in vitro* culture.

1. INTRODUCTION

Butia capitata (pindo palm) is a native and endemic palm of the Brazilian Cerrado, increasingly valued for its culinary and ornamental uses, as well as its ecological importance as a food source and shelter for wildlife (Sá et al., 2020; Barbosa et al., 2021; Sant'Anna-Santos, 2021). These applications justify cultivation and restoration projects using this species; however, such initiatives remain limited due to difficulties in seedling production. *B. capitata* seeds exhibit dormancy (Magalhães et al., 2013), leading to slow, uneven, and low germination rates (Magalhães et al., 2013; Oliveira et al., 2013), which limits large-scale seedling production.

Seed dormancy in *B. capitata* is currently classified as morphophysiological (Soares et al., 2021). This type of dormancy occurs in diaspores with underdeveloped (i.e., small, <1% of the overall diaspore size) embryos, which also have low growth potential (physiological dormancy) (Baskin and Baskin, 2014). In this case, germination is only completed after a phase of embryo growth within the diaspore, until it acquires the strength to overcome the resistance of the adjacent tissues (Baskin & Baskin, 2021; Jaganathan, 2021). The diaspores (pyrenes) of *B. capitata* form a complex system. In addition to the operculum - seed structure composed of the opercular integument and micropylar endosperm - embryo growth is also restricted by the germination pore plate, a lignified tissue of the pericarp (Magalhães et al., 2013; Carvalho et al., 2015; MazzottinidosSantos et al., 2018; Soares et al., 2021).

The most common method for overcoming dormancy in *B. capitata* seeds involves mechanical removal of the operculum, allowing the seed to be exposed within the endocarp. Removing these structures results in high germination rates in less than a week (Oliveira et al., 2013; Dias et al., 2017; Soares et al., 2021). The use of isolated embryos, through in vitro culture, is another way of overcoming morphophysiological dormancy (Magalhães et al., 2013; Baskin & Baskin, 2021; Goeten et al., 2024), which involves developing immature or mature embryos under aseptic conditions and in nutrient media to obtain viable plants (Goeten et al., 2024). These methods, however, are costly, labor-intensive, and prone to microbial contamination, highlighting the need to combine them with other techniques to improve efficiency.

Dry seed storage can induce physiological and structural changes in the seed and/or pyrene, known as after-ripening, which lead to dormancy release (Bewley et al., 2013; Baskin & Baskin, 2021; Jaganathan, 2021). Physiological changes may

promote gibberellin (GA) synthesis and abscisic acid (ABA) degradation, resulting in a hormonal balance favorable to germination (Bicalho et al., 2019; Pinto et al., 2024). Structural modifications may also occur, primarily facilitating embryo growth and reducing resistance in the tissues surrounding the embryo (Baskin & Baskin, 2021; Jaganathan, 2021; Soares et al., 2021). On the other hand, storage may lead to seed deterioration, as chemical processes continue in dry seeds, resulting in vigor loss, reduced germination rates, and increased mortality (Sousa et al., 2017; Pinto et al., 2024). In oil-rich seeds such as those of *B. capitata*, these processes are associated with the peroxidation of abundant lipid reserves, which may be oxidative signaling (Bicalho et al., 2015) or cell membrane damage caused during seed rehydration (Sousa et al., 2017; Gonçalves et al., 2020; Pinto et al., 2024). However, few in-depth studies have evaluated the effects of storage on germination and viability in palm seeds.

Another important factor during seed storage is the environmental condition of the storage site. Freezing and refrigeration temperatures effectively preserve seed quality in Cerrado palm species (Ribeiro et al., 2012; Dias et al., 2016; Saleh et al., 2017). In contrast, higher temperatures may reduce seed viability and vigor (Ribeiro et al., 2012; Dias et al., 2015; Saleh et al., 2017). Under such conditions, seed deterioration may result from increased oxidative stress and reduced efficiency of the antioxidant system during storage (Bailly, 2019; Souza et al., 2022). Information on the effects of storage conditions on seed viability, vigor, and dormancy over time is essential for large-scale seedling production of *B. capitata*. Additionally, this knowledge has ecological relevance, as it enables inferences with seed bank dynamics in the soil and adaptive mechanisms of *B. capitata* to the Cerrado environment, a biome strongly characterized by climatic seasonality (Soares et al., 2021; Souza et al., 2022).

This study aimed to evaluate how different storage conditions affect the germination of *B. capitata* seeds. To do so, we sought to answer the following questions: (I) What is the influence of storage on seed germination, physiological quality, and structural integrity? (II) Which storage condition (shade on paper bags under laboratory conditions; in moist sand in a greenhouse, and in a refrigerator at 10 °C) is most effective in preserving seed physiological quality?

2. MATERIALS AND METHODS

2.1. Collection of plant material and pyrene storage

Fruits were collected from *B. capitata* mother plants in the germplasm bank located in the municipality of Montes Claros, northern Minas Gerais, Brazil (16°40'54.3"S, 43°50'21.5"W). Pyrenes (seeds enclosed by the endocarp, which constitutes the species' dispersal unit) were obtained by mechanically removing the exocarp and mesocarp, then treated with a fumigant insecticide containing aluminum phosphide (Gastoxin® B57) for seven days.

Pyrenes were stored for 150 days in a shaded, well-ventilated location, with temperature and relative humidity ranging from 22 to 27 °C and 50 to 55%, respectively (INMET, 2024). At 15, 30, 60, 90, 120, and 150 days of storage, seeds were extracted from the pyrenes using a hammer. Seeds showing injuries, insect damage, defects from the extraction process, malformation, shriveling, or necrosis were discarded. The experiment followed a completely randomized design, with storage duration as the treatment factor.

2.2. Assessment of moisture content and germination

Five replicates of 20 seeds, obtained after each storage period, were used to assess moisture content and germination. Moisture content was determined based on the ratio of fresh to dry seed mass after dehydration in an oven at 105 ± 3 °C for 24 hours (Brasil, 2009). Seeds were disinfected with sodium hypochlorite and alcohol and treated with the fungicides carboxin (100 g L^{-1}) and thiram (100 g L^{-1}) (Vitavax Thiram®), following the method of Oliveira et al. (2013). Next, the operculum was removed from the seeds (to break dormancy), and they were sown in transparent polyethylene trays filled with medium-grade vermiculite moistened with distilled water to 80% of its water-holding capacity (Oliveira et al., 2013; Dias et al., 2017). The trays were kept in a BOD germination incubator at 30 °C with a 12-hour photoperiod. Seeds were evaluated daily for 30 days, and germination was recorded when the cotyledonary petiole protruded at least 2 mm above the seed surface. Germination speed index (GSI) was calculated as the sum of the ratio between the number of seeds germinated each day and the number of days after sowing (Maguire, 1962), according to the following formula: GSI = (x1/d1 +..... xn/dn), X: number of germinated seeds and d: number of days after sowing.

2.3. Quantification of malondialdehyde (MDA) as an estimative of lipid peroxidation

Embryos (30 mg) from seeds stored for 15, 30, 60, 90, 120, and 150 days were macerated in liquid nitrogen. Four replicates were mixed with 1.5 mL of 1% (v/v)

trichloroacetic acid (TCA) buffer, vortexed for 2 minutes, and centrifuged at 12,000 rpm for 15 minutes. Then, 1 mL of the supernatant was pipetted and added to 3 mL of 0.5% thiobarbituric acid (TBA). The mixture was incubated in screw-cap tubes in a thermostatic water bath at 95 °C for 60 minutes on a heating plate. The tubes were cooled in an ice bath, followed by centrifugation at 9,000 rpm for 10 minutes. Absorbance was measured at 532 and 600 nm using a spectrophotometer (Shimadzu UV-1800 model). MDA values were calculated using the formula: $\left\{\frac{(ABS532-ABS600)}{155000}\right\} * 10^6$; where A_{532} represents the maximum absorbance of the MDA-TBA complex at 532 nm, A_{600} corrects for non-specific interferences, and 155,000 is the molar extinction coefficient of MDA. Results were expressed in nanomoles per gram of fresh weight (Health & Packer 1968, adapted).

2.4. Membrane functionality estimation – Electrical conductivity assessment

Twenty seeds per replicate (five replicates) from the 15, 90, and 150 days storage periods were placed in 200 mL of distilled water in beakers and kept at room temperature with constant aeration for 72 hours. During the imbibition period in water at 12, 24, 36, 48, 60, and 72 hours the electrical conductivity of the seed leachate in the beakers was measured using a conductivity meter (LUTRON PCD-432 model, manufactured in the United Kingdom), as reported by Dias et al. (2024).

2.5. Dormancy intensity estimation – Operculum resistance assessment

Operculum resistance was measured by determining the force required for its displacement, following the method of Mazzottini-dos-Santos et al. (2018), simulating the force exerted by the embryo in seeds stored for 15, 30, 60, 90, 120, and 150 days. For this, seeds were transversely sectioned just below the operculum region. This cut exposed the embryo, which was removed with forceps to reveal the inner surface of the operculum and allow insertion of the measuring tip of a dynamometer (Impac model IP90DI). The values were expressed as Nmm^{-2}.

2.6. Pyrene storage conditions and in vitro embryo culture

Seeds were extracted from five replicates of 10 pyrenes using a manual bench vise and used to determine moisture content by the oven-drying method, as previously described. Another ten replicates of 10 seeds were disinfected with 1% sodium hypochlorite for 10 minutes. In a laminar flow chamber, embryos were extracted using scalpels and placed in a 100 mg/L ascorbic acid solution to prevent oxidation. After disinfection in 0.5% sodium hypochlorite solution for 10 minutes and rinsing three times with distilled autoclaved water, embryos were inoculated into test tubes (7.5 × 1 cm) containing 2 mL of culture medium composed of: MS salts (Murashige & Skoog, 1962) at 75% of the original concentration; 0.4 mg/L thiamine; 1 mg/L pyridoxine; 0.5 mg/L nicotinic acid; 100 mg/L myo-inositol; 0.5 g/L hydrolyzed casein; 3 g/L activated charcoal; 30 g/L sucrose; 6 g/L agar; and pH adjusted to 5.7 (Magalhães et al., 2011). After inoculation, the tubes were wrapped in aluminum foil and kept in the dark in a growth chamber at 30 °C.

Additional pyrenes were stored under three conditions: in the shade on paper bags (porous packing - allows gas and moisture exchange with the environment) under laboratory conditions; buried in moist sand in a open greenhouse; and in a refrigerator (10 ± 1°C; 35 ± 5 % RH) sealed in polyethylene bags (thickness 200 μm). The temperature and relative humidity of the air, in the greenhouse conditions, varied, respectively, from 11.1 to 37.1 ºC and 15 to 96% and the substrate in which the pyrenes were buried was kept constantly moist, with daily irrigation. The temperature in the laboratory was maintained at 25 ºC ± 3ºC. At 30, 90, 150, 210, and 270 days of each storage condition, ten replicates of ten pyrenes were sampled, and the embryos were isolated, inoculated, and cultured under the conditions previously described. The experiment followed a factorial design of 3 (storage methods) × 5 (storage durations), with time zero as an additional treatment. Each culture experiment followed a completely randomized design, with 10 replicates of 10 test tubes, each containing a single embryo.

After 30 days, the tubes were removed from the growth chamber, and the embryos were evaluated for cotyledonary petiole elongation - considered an indicator of germination - and for seedling development traits, including leaf sheath emergence and primary root formation. Elongation was recorded when embryo length exceeded 1 cm.

2.7. Statistical analysis

In the seed study, data were subjected to analysis of variance (ANOVA), and means were compared using Tukey's test at a 5% significance level. A regression equation was also

applied to moisture content and MDA. In the in vitro culture experiment, data were collected by counting the number of embryos or seedlings exhibiting each event, calculated as percentages, and subsequently transformed using the arcsine square root transformation [arcsine$(x/100)^{1/2}$]. As in the previous study, data were subjected to analysis of variance and Tukey's test at a 5% significance level. In addition, treatments were compared with the control using Dunnett's test at a 5% significance level.

3. RESULTS

3.1. Pyrene storage

3.1.1. Assessment of moisture content, germination, and vigor

Seed moisture content (6.5%) decreased over time, reaching its lowest level by 120 days. After that point, moisture stabilized, reaching values below 4.7% by the end of the 150-day storage period (Figure 1).

Seed germination of *B. capitata* remained unchanged up to 90 days of storage, with an average germination rate of 62%. However, from 120 days of storage onward, a sharp decline in germination rate was observed, reaching the lowest value (16%) at the final evaluation time point (Figure 2a). Similarly, the germination speed index (GSI) showed no significant differences up to 90 days, with an average of 2.80. Between 120 and 150 days, GSI reduced significantly, with an average of 1.07 (Figure 2b). All non-germinated seeds were found to be contaminated by pathogenic microorganisms.

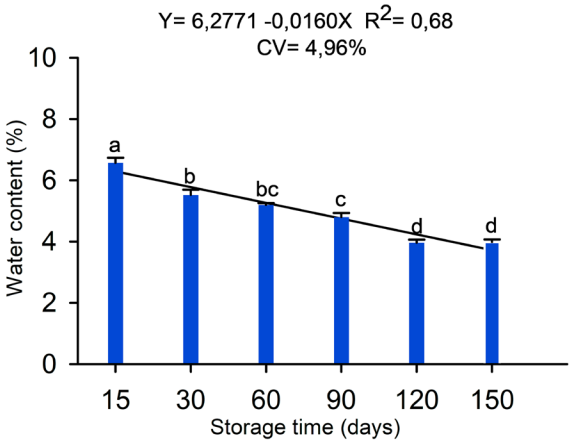

Figure 1. Moisture content of *B. capitata* seeds extracted from pyrenes stored in a shed for 15, 30, 60, 90, 120, and 150 days. Different letters indicate statistically significant differences by Tukey's test ($P < 0.05$). Vertical bars (black) represent the standard error of each mean. n = 30.

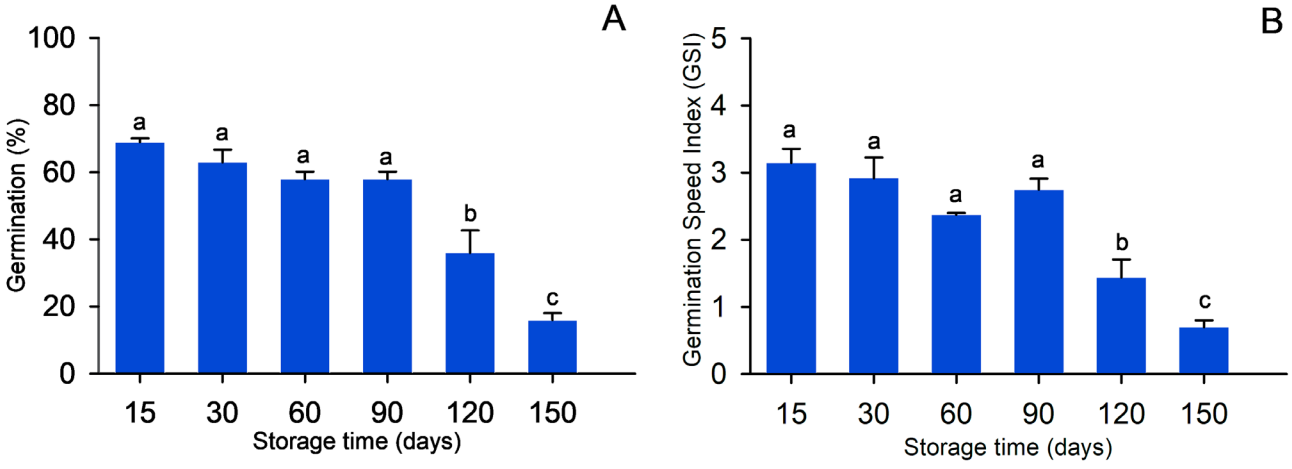

Figure 2. Germination percentage (a) and germination speed index (GSI) (b) of *B. capitata* seeds extracted from pyrenes stored in a shed for 15, 30, 60, 90, 120, and 150 days. Different letters indicate statistically significant differences by Tukey's test ($P < 0.05$). Vertical bars (black) represent the standard error of each mean. n = 30.

3.1.2. Quantification of malondialdehyde (MDA) as an indicator of lipid peroxidation

MDA content, an indicator of lipid peroxidation, was significantly affected by seed storage. MDA concentration did not differ during the initial evaluation periods up to 60 days; however, a significant increase was observed at 90 days compared to 15 days of storage. At 120 and 150 days of storage, high MDA levels were detected (Figure 3).

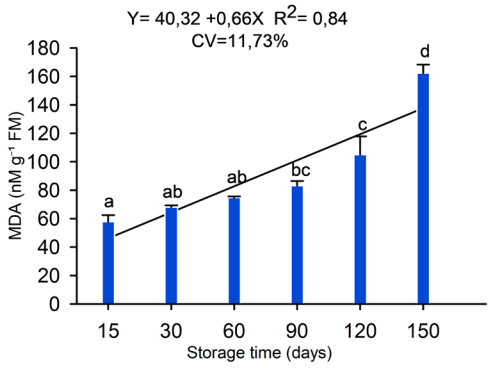

Figure 3. Malondialdehyde (MDA) content in embryos of *B. capitata* seeds stored in a shed for 15, 30, 60, 90, 120, and 150 days. Different letters indicate statistically significant differences by Tukey's test ($P < 0.05$). Vertical bars (black) represent the standard error of each mean. n = 30.

3.1.3. Estimation of membrane functionality – Electrical conductivity assessment

Seeds maintained control over solute leakage up to 90 days of storage; however, a significant increase in electrical conductivity was observed at 150 days (Figure 4a). During the seed imbibition period, electrical conductivity gradually increased, with a marked rise after 36 hours (Figure 4b).

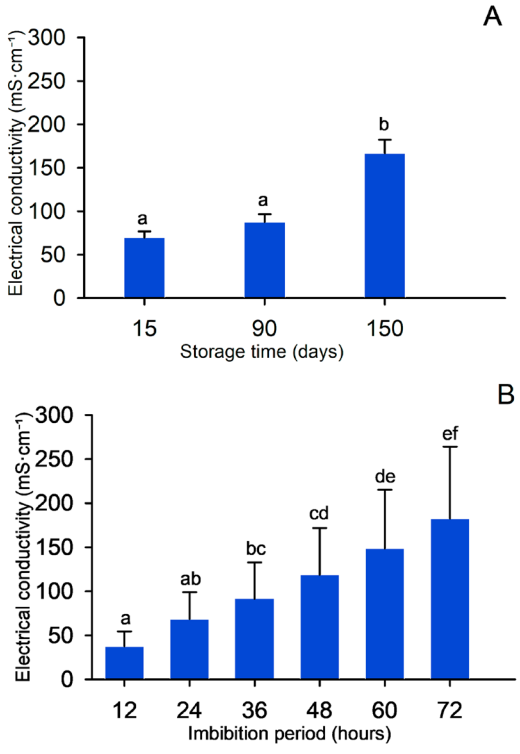

Figure 4. Electrical conductivity of *B. capitata* seeds stored in a shed for 15, 60, and 90 days (a), and during the imbibition period in water at 12, 24, 36, 48, 60, and 72 hours (b). Different letters indicate statistically significant differences by Tukey's test ($P < 0.05$). Vertical bars (black) represent the standard error of each mean. n = 15.

3.1.4. Dormancy intensity estimation – Operculum resistance assessment

Dormancy intensity, estimated by operculum rupture resistance (Figure 5), remained unchanged up to 90 days of storage. After this period, operculum resistance decreased, indicating lower dormancy intensity at the last two time points.

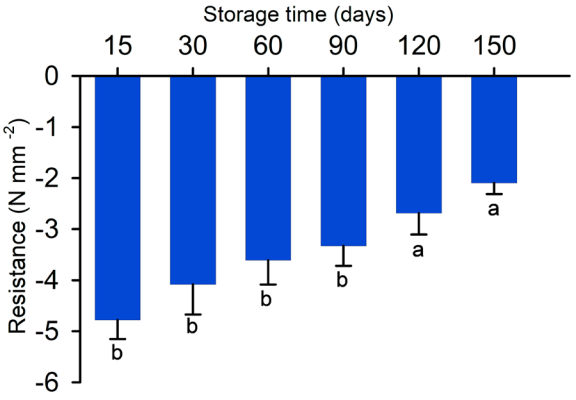

Figure 5. Operculum rupture resistance in *B. capitata* seeds stored in a shed for 15, 30, 60, 90, 120, and 150 days. Different letters indicate statistically significant differences by Tukey's test ($P < 0.05$). Vertical bars (black) represent the standard error of each mean. n = 30.

3.2. Pyrene storage conditions and in vitro embryo culture

Initially, the seeds showed the same moisture content (6.5%) as previously reported. All evaluated traits were significantly affected by storage duration ($P < 0.01$), storage method ($P < 0.01$), and their interaction ($P < 0.01$). Ninety-two percent of embryos from *B. capitata* seeds before storage showed cotyledonary petiole elongation (Figure 6a). Storage in sand resulted in lower elongation than refrigerated storage throughout the storage period, and lower than shaded storage at 30 days. Shaded and refrigerated storage produced similar results up to 30 days and did not differ from time zero; however, after this period, refrigeration was superior. All treatments led to viability loss over time, but the decline was slower under refrigeration and occurred only after 270 days.

Leaf-sheath emergence was observed in 36% of seedlings obtained from seeds at the initial condition. Shaded storage of pyrenes resulted in a higher percentage of leaf sheath emergence at 30 days compared to the other treatments, followed by a decline through 270 days. From 90 days onward, refrigeration led to a higher percentage of leaf-sheath emergence than the other conditions, with only a slight decline over time. Storage in sand resulted in reduced leaf

sheath emergence for up to 150 days, with no significant variation thereafter. Sand storage at all time points and shaded storage from 90 days onward resulted in lower values compared to time zero (Figure 6b).

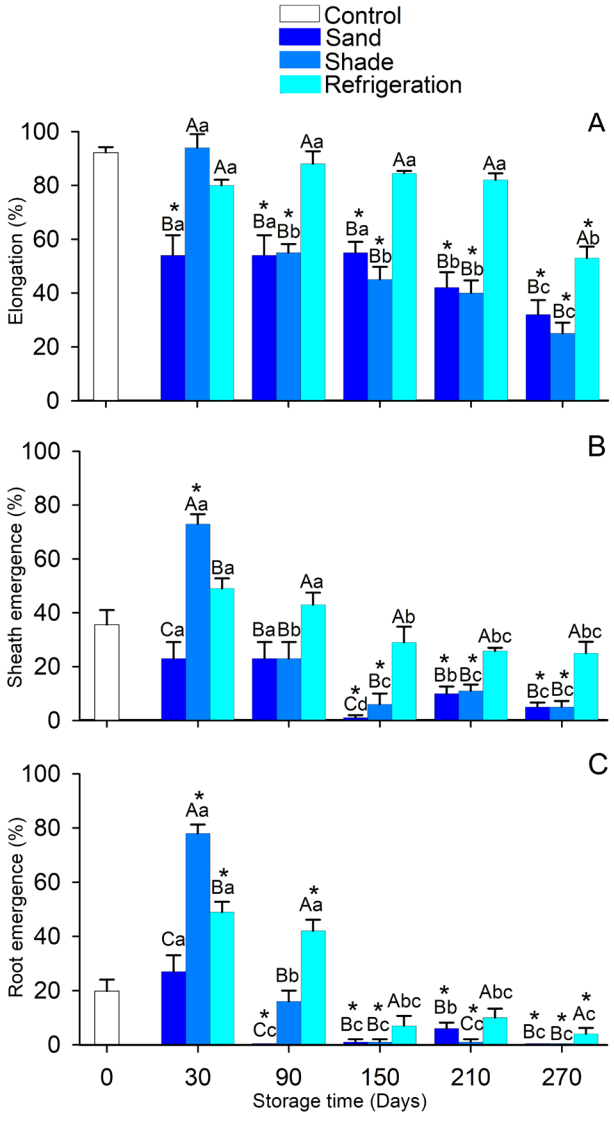

Figure 6. Cotyledonary petiole elongation (a), presence of leaf sheaths (b), and primary root emergence (c) in embryos cultured *in vitro* as a function of storage methods (sand, shade, and refrigeration) and durations (0, 30, 90, 150, 210, and 270 days) in shed-stored *B. capitata seeds*. Different letters indicate statistically significant differences according to Tukey's test ($P < 0.05$). Uppercase letters compare storage methods within each time point, while lowercase letters compare time points within each storage method. Asterisks indicate statistically significant differences according to Dunnett's test ($P < 0.05$) between treatments and the control. Vertical bars (black) represent the standard error. n = 160.

In embryo culture conducted before storage, 20% of seedlings developed roots. The best results were reached with shaded storage at 30 days. At this time point, root emergence was higher in the refrigeration and shaded treatments compared to time zero. At 30 and 90 days, refrigeration promoted greater root emergence, while shaded storage reduced rooting capacity. From 150 days onward, no differences were observed among the storage methods. However, results from refrigeration did not differ significantly from those at time zero, whereas sand and shaded storage were inferior

4. DISCUSSION

4.1. Changes in seed physiological quality and germination over time and storage conditions

Storage conditions strongly influenced the germination and physiological quality of *B. capitata seeds*. Even after 15 days of storage, seeds showed a decreasing dehydration pattern until 90 days, after which only minor variation occurs (Figure 1). This species disperses its seeds with a moisture content of about 30%, but under shaded conditions, it drops to 6% after 30 days post-harvest (Dias et al., 2015), which aligns with our findings. However, after this period, dehydration continues until the moisture content reaches between 4% and 3%, defined as the minimum moisture range for *B. capitata* seeds when dried in an oven and with silica gel (Dias et al., 2015). Air temperature (T) and relative humidity (RH) affect seed moisture content, especially in open environments and porous packaging (Hay et al., 2022a; Nadarajan et al., 2023). Conversely, oil-rich seeds, are less influenced by T and RH variations when stored in shaded or open environments such as those of *B. capitata* with lipid content above 31% (Barbosa et al., 2021) and other Cerrado species with high lipid content (Ribeiro et al., 2012; Pinto et al., 2024). This may explain the minimal variation in moisture content after 120 days when the minimum water content was reached. However, T and RH changes may contribute to oxidative stress in *B. capitata*, affecting its longevity and germination, as reported in several studies (Zhu et al., 2021; Hay et al., 2022a; Hay et al., 2022b; Nadarajan et al., 2023).

The highest levels of physiological quality and germination in *B. capitata* seeds occur within 90 days of storage. During this period, the highest germination, vigor (associated with GSI), elongation, and emergence of leaf sheaths and roots were observed under uncontrolled storage conditions (Figures 2a-b, 6a-c). However, prolonged storage of *B. capitata* (over 90 days) reduces its physiological quality and germination capacity. A study evaluating *B. capitata* seeds under different storage conditions also detected low germination and the emergence of leaf sheaths and shoots in *in vitro* culture after 90 days of storage at room temperature, nearly 22°C

(Dias et al., 2015). This occurs due to oxidative stress that is not controlled by the antioxidant system, which causes degenerative transformations (cellular and molecular damage) in the seeds during storage (Souza et al., 2022; Dias et al., 2024; Pinto et al., 2024). Oxidative stress is exacerbated by the greater variation in temperature and humidity in open environments without control of these factors (Zhu et al., 2021; Hay et al., 2022a; Hay et al., 2022b; Nadarajan et al., 2023), such as those used in this study, shade and greenhouse – sand, in relation to the refrigerator. Therefore, this explains the lower viability and vigor of *B. capita* seeds stored in these two environments, especially after 90 days, when the antioxidant system is likely unable to control the intense oxidation process.

Low temperatures promote greater longevity in *B. capitata* seeds. Refrigeration increases percentages of elongated embryos and leaf sheath emergence compared to the other treatments, especially after 90 days (Figures 6a-b). Cold storage has been shown to better preserve germination capacity and vigor in oil-rich seeds of native Cerrado palm species and those of the genus *Butia*, as reported for *A. aculeata* (Ribeiro et al., 2012) and *Attalea speciosa* (Saleh et al., 2017). However, temperatures above 22°C have led to seed deterioration in these species, as well as in *B. capitata*, as observed in in vitro culture studies, characterized by low germination and poor emergence of shoots and roots (Ribeiro et al., 2012; Dias et al., 2015; Saleh et al., 2017; Soares et al., 2021). Thus, reducing temperature slows down metabolism and oxidative processes, extending seed longevity (Dias et al., 2015; Saleh et al., 2017; Goeten et al., 2024).

Storage of *B. capitata* seeds at temperatures between -18°C and -10°C results in a significant loss of embryo viability (Dias et al., 2015). Thus, the seeds of this species are classified as freezing-intolerant and exhibiting intermediate behavior, according to the classification by Hong and Ellis (1996). In the cited study, seeds were frozen with embryos containing high moisture, which can lead to crystal formation and cellular injury (Dias et al., 2015). In our study, freezing temperatures were not used. Furthermore, seeds enclosed by the hard endocarp (pyrenes) are protected during storage from environmental factor variations (Carvalho et al., 2015; Sousa, 2017a, b), which may mitigate the deleterious effects of low temperatures and promote longevity. In this regard, the role of the endocarp must be further investigated, both in seed management and in the species' reproductive ecology.

4.2. Oxidative stress, longevity, and dormancy

Low germination of *B. capitata* seeds after 90 days of storage is associated with the inability to control oxidative stress. Seeds stored beyond this period generate high MDA concentrations (Figure 3) and elevated electrical conductivity (EC) (Figure 4), both linked to reduced germination (Figure 2a). During seed drying (post-ripening), water stress resulting from dehydration often leads to accumulation of reactive oxygen species (ROS), which can cause high oxidative stress if the seed's antioxidant system is inefficient at removing them (Bailly, 2019; Dias et al., 2024). Hydrogen peroxide (H_2O_2) and superoxides are among the main ROSs, and their accumulation in cells causes oxidative stress. However, when controlled, H_2O_2 can have a positive effect by reducing abscisic acid (ABA) levels and overcoming dormancy (Bicalho et al., 2019; Dias et al., 2024; Pinto et al., 2024). On the other hand, the enzymes ascorbate peroxidase (APX), catalase (CAT), and superoxide dismutase (SOD) regulate ROS accumulation, such as superoxide and hydrogen peroxide, promoting cell detoxification (Bailly, 2019; Bicalho et al., 2019; Dias et al., 2024; Pinto et al., 2024). Therefore, the inefficiency of the antioxidant system, the increased production of MDA as a result of lipid peroxidation, and solute leakage (EC) could be the causes of low germination and vigor in *B. capitata* seeds stored after 90 days, as observed in the species' embryos under water stress (Gonçalves et al., 2020).

Storage promotes dormancy reduction in *B. capitata* seeds. Operculum resistance, one of the components of seed dormancy in palms, decreases after 90 days (Figure 5). The dormancy of palm seeds, including *B. capitata*, is classified as morphophysiological, i.e., it requires embryo growth and rupture of adjacent tissues (Baskin & Baskin, 2021; Soares et al., 2021). The tissues that prevent cotyledonary petiole protrusion in palms are the operculum and germination pore plate. When isolated seeds are used, the main barrier to germination is the operculum, which, after displacement, allows cotyledonary petiole protrusion (Oliveira et al., 2013; Dias et al., 2017; Soares et al., 2021). Therefore, a reduction in operculum resistance can promote cotyledonary petiole growth and overcome dormancy. Storage has been shown to reduce tissue resistance in some species, thereby facilitating germination (Silva et al., 2007; Sousa et al., 2017; Souza et al., 2022; Pinto et al., 2024). However, even if dormancy is overcome, low germination rates occur due to seed deterioration, as observed in another Cerrado species, *C. brasiliense* (Sousa et al., 2017; Pinto et al., 2024). In this regard, shorter storage intervals must be evaluated to identify periods and conditions that reduce dormancy intensity while also enhancing seed viability and vigor. This information is valuable for understanding the species' ecological strategies and establishing protocols for large-scale seedling production.

5. CONCLUSIONS

Recently dispersed *Butia capitata* seeds stored for up to 90 days maintain their germination capacity and high physiological quality. Dormancy, associated with the operculum, is reduced after 90 days of storage; however, beyond this period, deterioration increases, decreasing seed viability and vigor.

Pyrenes stored under refrigeration preserve germination capacity, as well as embryo leaf sheath and root emergence, for a longer period.

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Renan Ribeiro Silva: Formal analysis (Equal), Investigation (Equal).
Silma da Conceição Neves: Investigation (Equal), Methodology (Equal).
Leonardo Monteiro Ribeiro: Formal analysis (Equal), Investigation (Equal), Supervision (Equal), Writing - review & editing (Equal).
Paulo Sergio Nascimento Lopes: Conceptualization (Equal), Formal analysis (Equal), Funding acquisition (Equal), Methodology (Equal), Supervision (Equal), Writing - review & editing (Equal).

DATA AVAILABILITY

The entire dataset supporting the results of this study was published in the article itself.

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