ASIAN JOURNAL OF AGRICULTURE
Volume 10, Number 1, June 2026
Pages: 11

E-ISSN: 2580-4537
https://doi.org/10.13057/asianjagric/g100107

Monitoring of seed viability and longevity after storage in Purwodadi Botanic Garden Seed Bank, Pasuruan, Indonesia

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Manuscript received: 16 September 2025. Revision accepted: 23 January 2026.

Abstract. *Enfaith FB, Oktavia GAE, Lestari DA, Ariyanti EE. 2026. Monitoring of seed viability and longevity after storage in Purwodadi Botanic Garden Seed Bank, Pasuruan, Indonesia. Asian J Agric 10: g100107. https://doi.org/10.13057/asianjagric/g100107.* Seed longevity is determinant of efficiency of storage practice. Seed viability after storage needs to be monitored to determine seed longevity. Seed viability of selected seed in the Purwodadi Botanic Garden (PBG) Seed Bank, Pasuruan, Indonesia, was monitored to predict the seed longevity after storage. The material used was selected seed species that have been stored in low temperature storage (-20°C) in hermetic storage at the Purwodadi Botanic Garden Seed Bank since 2016 (7 years storage), i.e., *Aleurites moluccana*, *Cassia grandis*, *C. javanica*, *Colona scabra*, *Hura crepitans*, *Ixora miquelii*, *Pterospermum diversifolium*, *Sterculia foetida* and *Swinglea glutinosa*. Seeds from each species were sown in sand as the planting medium, were then observed to perceive the germination percentage, the seed viability percentage, and the seed longevity. The results showed that all selected seeds experienced a decrease in germination percentage and even lost their ability to germinate. Seed longevity varies from very short with a decreasing rate of >30% (*H. crepitans*, *I. miquelii*, *P. diversifolium*, *S. glutinosa* and *S. foetida*), short with a decreasing rate of 15-30% (*C. javanica* and *C. scabra*), medium with a decreasing rate ranging from 4-15% (*C. grandis*), to long-lived seeds with a decreasing rate of <5% (*A. moluccana*). SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted to determine conservation strategies for seeds stored in the PBG Seed Bank. The result was that the appropriate conservation strategy for the PBG Seed Bank was assertive or proactive.

Keywords: Decreasing rate, germination, storage, SWOT analysis

Abbreviations: ISTA: International Seed Testing Association, PBG: Purwodadi Botanic Garden, SWOT: Strengths, Weaknesses, Opportunities and Threats

INTRODUCTION

Seed banks represent a key approach to ex-situ conservation, enabling the long-term preservation of plant genetic material under controlled low-temperature conditions. The compact size of seeds and their minimal space requirements make them particularly suitable for efficient storage (Ray and Bordolui 2021). Effective seed handling and maintenance protocols are fundamental to ensure the long-term conservation of plant genetic resources. According to Kumar et al. (2024), seed banks play a vital role in plant breeding programs and the prevention of extinction, serving as insurance against environmental changes and as a source of genetic material for scientific research and education. However, long-term seed storage poses the risk of declining seed quality, which may affect seed longevity. Therefore, regular monitoring of storage conditions is essential to maintain seed viability throughout the storage period.

Seed longevity is influenced by both external factors, such as storage conditions, and internal factors, including seed characteristics. These factors contribute to seed deterioration. External factors include storage temperature and humidity, microorganisms, and mechanical damage during handling and storage. External factors are related to the environmental factors of seed storage (Tan et al. 2025). Internal factors encompass genetics (Ramtekey et al. 2022), initial seed quality, the compositions of seeds (such as hormones, proximate content, and antioxidant capacity), and reactive oxygen species (Pirredda et al. 2024).

So far, seed viability monitoring is a procedure established by seed banks to assess whether stored seeds are still of good quality or need regeneration to prevent the loss of genetic resources. The primary goal in seed collection management is to maintain seed viability; seeds should be stored under conditions that allow them to remain viable for as long as possible and should be revived before they lose their capability to germinate. Seed viability monitoring is typically conducted through germination tests (Hay and Whitehouse 2017). Decisions following the monitoring process are made based on seed viability thresholds (Wijnker et al. 2025). Pratiwi et al.

(2022) stated that the seeds from Annonaceae species stored in the seed bank require a change in storage method based on seed viability monitoring results. More than 75% of the seeds from *Polyalthia longifolia* were empty after storage. This indicates that the current storage method is not compatible with *P. longifolia.* In general, seed viability gradually declines over time and tends to decrease more rapidly as seed age increases. *Trema orientalis* seeds, classified as intermediate seeds, experienced a viability decrease of over 50% after six months of storage (Yuniarti et al. 2018). The rate of viability loss varies among seed species, depending on both storage environmental factors and the genetic characteristics of the seeds (Corbineau 2024). From a study conducted by Lee et al. (2013) that compared seed viability among 42 species after ten years of storage in a medium-term storage complex (4°C, 30-40% RH) at the National Agrobiodiversity Center (NAC), a Korean gene bank, the results showed that the decrease in seed viability varied greatly.

In addition to supporting decision-making for seed storage, seed viability monitoring can also be used to predict seed longevity. The lifetime or longevity of a seed refers to the period during which the seed can stay viable (Nadarajan et al. 2023). Seed longevity varies between species and even among populations of the same species since it is a complex characteristic that is affected by various factors, as stated by Han et al. (2023). Seed longevity is a tool to estimate seed aging (Fu et al. 2015). Furthermore, Fenollosa et al. (2020) maintained that assessing seed longevity and vigor is critical for proficient ex-situ biodiversity conservation in gene banks but may also have prospective purposes for comprehending ecological processes and in situ biodiversity conservation.

Successful seed storage is crucial for the conservation of plant species. Seeds stored in the Purwodadi Botanic Garden (PBG) Seed Bank, Pasuruan, East Java, Indonesia, have been stored for over five years. This research is necessary as a first step to ensure the success of the PBG Seed Bank. The seeds stored in the PBG Seed Bank have been maintained for more than five years. Therefore, seed viability test is necessary to ensure that seeds from selected species in the PBG Seed Bank remain of sufficient quality for long-term storage. This research aimed to monitor the viability and predict the longevity of selected seed species stored in the PBG Seed Bank. The hypothesis of this study is that seed viability, as influenced by seed storage characteristics, will decline over time, thereby reducing seed longevity. These findings will inform improved conservation strategies for seed banks, especially at the PBG.

MATERIALS AND METHODS

Study area

This research was conducted from August 2023 to January 2024 at the seed banks laboratory and the Bidara greenhouse of Purwodadi Botanic Garden, National Research and Innovation Agency (BRIN), Pasuruan, East Java, Indonesia. The seeds monitored for viability and used to predict longevity were selected species that had been stored under low-temperature conditions (-20°C) in hermetic storage (sealed aluminium foil bags) at the PBG Seed Bank since 2016. It became the first seed collection used for viability monitoring at the PBG Seed Bank (Table 1 and Figure 1). The seeds of selected species were harvested from the living collection conserved in the PBG, which were shown by the origin of seeds in the block of the PBG area (Table 1). After harvesting, the seeds underwent processing steps, including rind peeling, pulp removal, washing, and drying. These processing stages were adjusted to the characteristics of each species. The prepared seeds were then subjected to initial sowing to determine their initial germination percentage. Before storage, the seeds' moisture content after drying was measured using a TinyTag data logger, targeting a range of 10-15%. The seeds were subsequently stored in sealed aluminium foil bags in the freezer at a temperature of -20ºC. Currently, the storage protocol remains conventional, and seed characterization prior to storage has not yet been performed. The selected seed species were chosen because of their abundance in the PBG Seed Bank.

Table 1. Selected seed material that has been stored in freezer storage since 2016

Collection number	Species	Family	Harvest date	Storage date	Origin of seeds (block)	Initial germination (%)	SSB
PL 162	*Aleurites moluccana* (L.) Willd	Euph.	25/8/2016	13/9/2016	XX.6	0	O
PL 086	*Cassia grandis* L. f.	Caes.	13/6/2016	27/7/2016	XXI.A.3	10	O
PL 159	*Cassia javanica* L.	Caes.	25/8/2016	1/9/2016	XIV.E.	25	Op
PL 154	*Colona scabra* (Sm.) Burret	Malv.	26/7/2016	26/7/2016	XVI.H.43	23.33	≠
PL 171	*Hura crepitans* L.	Euph.	5/10/2016	7/10/2016	XII.A.7	100	O?
PL 174	*Ixora miquelii* Bremek	Rub.	22/7/2016	26/7/2016	X.A	80	≠
PL 037	*Pterospermum diversifolium* Blume	Sterc.	5/10/2016	7/10/2016	XVIII.B.13	100	≠
PL 211	*Sterculia foetida* L.	Sterc.	16/8/2016	22/9/2016	XXIV.E	100	Op
PL 186	*Swinglea glutinosa* (Blanco) Merr.	Rut.	26/2/2016	15/4/2016	V.B	100	Op

Note: PL: Purwodadi Lama, SSB: Seed Storage Behaviour (Based on Seed Information Database (2024)), O: Orthodox, Op: Orthodox probably, O?: Orthodox but is still questionable, ≠: Storage behaviour is unidentified

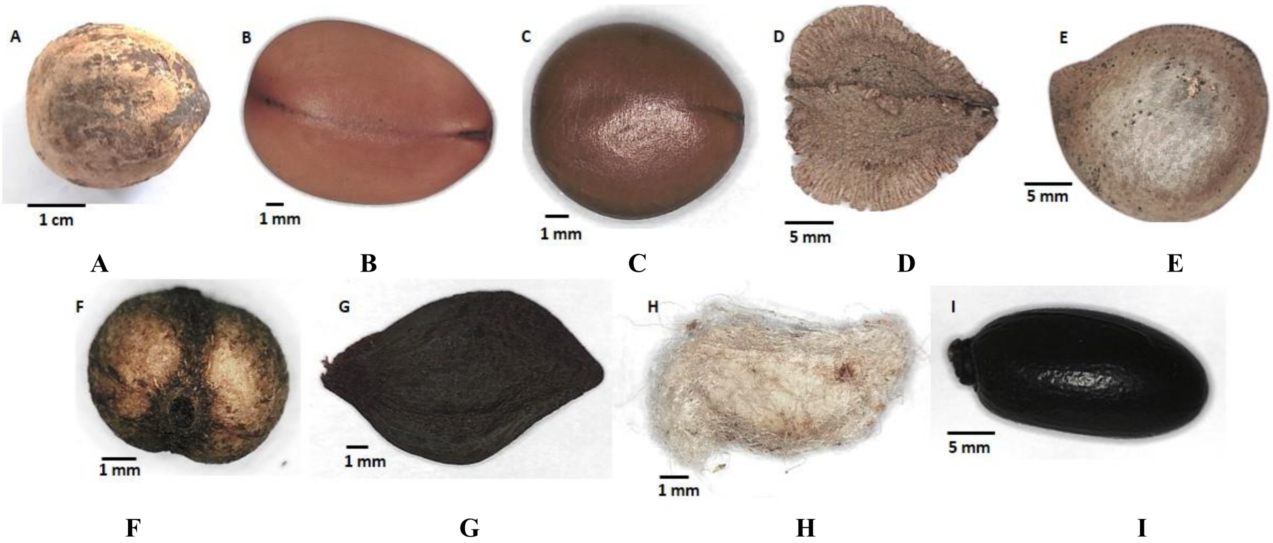

Figure 1. Morphology of selected seeds that have been stored in freezer since 2016. A. *Aleurites moluccana*, B. *Cassia grandis*, C. *Cassia javanica*, D. *Colona scabra*, E. *Hura crepitans*, F. *Ixora miquelii*, G. *Pterospermum diversifolium*, H. *Swinglea glutinosa* and I. *Sterculia foetida*

Procedures

Seed viability and longevity monitoring

Seed samples from the selected materials listed in Table 1. Twenty-five seeds per replication were used, with three replications per species (75 seeds in total). The seeds were sown in seedling trays filled with sand (lesti sand, a type of sand) as the planting medium, then observed and watered daily in the morning for up to 4 months of observation. Observation parameters were the number of germinated seeds to determine the germination percentage, the seed cut-test results at the end of the germination period to assess the seed viability percentage, and the rate of decline to estimate the seed longevity based on the method by Lee et al. (2013). Environmental conditions at the Bidara greenhouse PBG included an average temperature of 30.5°C, humidity of 70.32%, and light intensity of 5572 lux. Lesti sand, used as the planting medium, was not sterilized before sowing.

The cut-test was performed by vertically cutting seeds that failed to germinate during the observation period, using pruning shears or a scalpel, followed by examination of the condition of the embryo and endosperm (Lailaty et al. 2023). The results of the cut-test were categorized into four groups: fresh seeds (viable and healthy), empty seeds, infested seeds, and abnormal seedlings (Pratiwi et al. 2022).

SWOT analysis

Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was conducted to determine conservation strategies for the seeds stored in the PBG Seed Bank, especially for selected seed species observed. The SWOT analysis refered to Scolozzi et al. (2014) and went through the following stages: (i) Determining the factors to be compared, (ii) Identifying key internal and external factors to construct a hierarchical structure, (iii) Calculating and normalizing performance values to standardize the scale of key factors, and 4) Calculating the SWOT coordinate values for internal and external assessments.

Data analysis

Data on the number of germinated seeds were analysed descriptively to determine the percentage of seed germination using Equation 1 (Sutopo 2010), while the results of the cut-test were used to assess seed viability using Equation 2 (Davies et al. 2015). The decreasing rate data were categorized based on the comparison between the germination percentage at the initial storage time and after a certain storage period, to evaluate the rate of seed viability decline over time. Data on the percentage of initial and post-storage germination, as well as seed viability, were analysed descriptively using the mean and standard deviation. Variance analysis of the initial and post-storage germination percentages was conducted using RStudio. When significant differences were detected, Duncan's multiple range test was performed at a 95% confidence level.

$$\text{Germination percentage (\%)} = \frac{G}{X} \times 100\% \qquad [1]$$

$$\text{Seed viability (\%)} = \frac{G + F + A}{X - (E - I)} \times 100\% \qquad [2]$$

Whereas, G was the number of seeds were germinated, X was the number of seeds that were sown, F was the number of fresh seeds based on the cut-test result, A was the number of abnormal sprouts during germination, E was the number of empty seeds based on the cut-test result, and I was the number of infected seeds based on the cut-test result.

RESULTS AND DISCUSSION

Monitoring of seed viability and longevity of selected species after storage in the PBG Seed Bank can be used to determine further conservation strategies. Non-viable seeds during storage would be re-collected, while viable seeds will remain stored and monitored regularly. Based on this research, it can be seen that viability and longevity from each species vary and need different treatments to maintain their viability. The seed storage behaviour becomes one of the requirements for long-term seed storage.

Monitoring the germination percentage and predicting the longevity of selected seeds after storage

Based on the results of seed germination tests after storage, it can be seen that all selected seeds experienced a decrease in germination percentage and lost their ability to germinate (Figure 2). The seeds that experienced a decrease in germination percentage were *C. javanica, C. scabra, H. crepitans, I. miquelii, P. diversifolium*, and *S. foetida.* Meanwhile, the seeds that lost ability to germinate were *C. grandis* and *S. glutinosa.* In addition, *A. moluccana* seeds were unable to germinate either at the beginning of storage or after storage at low temperatures. The seeds that exhibited significant differences between the initial measurement and after storage belonged to all species except *A. moluccana*.

The observed germination percentage of the selected seed is related to the storage behaviour. According to the Seed Information Database, International Seed Testing Association (SID 2025a), *A. moluccana* seeds are classified as an orthodox seed, which can be stored for long periods up to 79 years of storage with a germination rate of 79% and may exhibit seed dormancy. Seed germination challenges are often encountered due to specific seed morphological traits that lead to dormancy, requiring special treatment to initiate germination (Sutopo 2010). According to Susilowati et al. (2019), *A. moluccana* seeds morphologically have the physical characteristics of a hard seed coat and have a shell-like shape. Based on monitoring results of *A. moluccana* seeds, it is likely that these seeds require specific pre-germination treatments to overcome dormancy.

Swinglea glutinosa seeds experienced a complete loss of germination capacity up to 0%. According to the Seed Information Database (SID 2025b), the storage behaviour of *S. glutinosa* seeds is categorized as orthodox probably, which indicates that the seeds are likely not truly orthodox and may instead be intermediate or recalcitrant. According to Lestari (2019), *S. glutinosa* seeds can only be stored in aluminum foil or silica-coated glass bottles at room temperature or in low-temperature storage (freezer) for 1 month, and their germination ability is lost if stored for 2 months. Therefore, *S. glutinosa* seeds are classified as a recalcitrant seed, which is not tolerant to long-term storage. Considering the research findings presented by Lestari (2019), alternative storage techniques are necessary to extend the shelf life of *S. glutinosa* seeds. A recommended strategy that can be given is to explore the use of cryopreservation techniques for storing *S. glutinosa* seeds, as suggested by Pence (1995) that unconventional storage techniques like cryopreservation provide the potential to keep tissues from recalcitrant seeds in a stable condition for extended durations. Ballesteros et al. (2020) stated that cryopreservation is suitable for long-term seed preservation. This storage technique applies not only to orthodox seeds but also serves as an alternative method for storing recalcitrant and intermediate seeds.

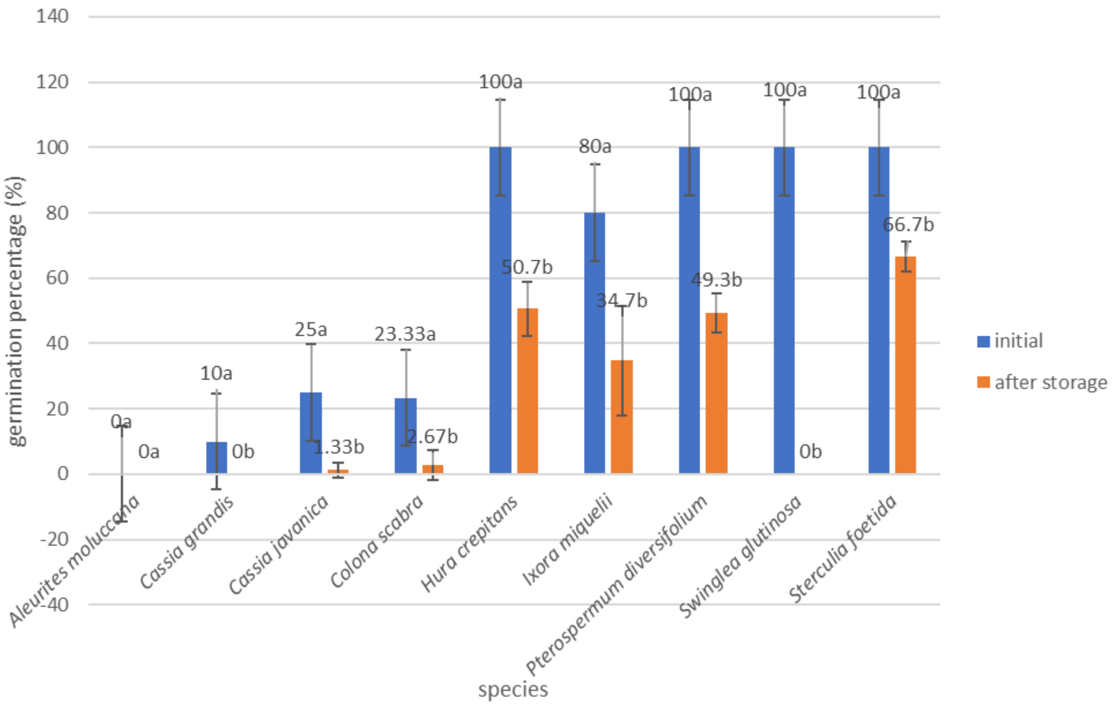

Figure 2. Germination percentage of selected seeds that have been stored in freezer storage since 2016. Error bars represent mean ± standard deviation. Different letters above bars indicate significant differences between initial and after storage based on DMRT test ($p<0.05$)

Seeds of *C. scabra*, *I. miquelii*, and *P. diversifolium* require preliminary testing to determine their storage behaviour before being stored at low temperatures. It is essential to determine the variation in seed storage behaviour prior to selecting an appropriate storage method, as seeds from different species will exhibit different storage responses (Hong et al. 1996). This testing can be conducted using the 100-seed test method (Pritchard et al. 2004; Wardani and Mimin 2020) or by following protocols developed by Hong and Ellis (1996). Such testing is important, particularly since these seeds still show some level of germination viability, although their germination percentage decreases after being stored at low temperatures for a certain period. Most species from the *Ixora* genus are categorized as orthodox seeds, such as *I. coccinea* (Shinde and Chavan 2017), *I. henryi, I. javanica*, and *I. linearifolia* (SID 2025c). *Cassia scabra* and *P. diversifolium* are classified as the winged seeds category. *Pterospermum acerifolium* and *P. semisagittatum* seeds have orthodox (?) seed storage behaviour (SID 2025d). *Pterospermum diversifolium* has a heterotypic synonym with *P. acerifolium* (POWO 2025), which suggests that the storage behaviour of *P. diversifolium* seeds is also included in orthodox (?) seeds. Orthodox (?) has a similar meaning to Op, where the seed storage behaviour is likely orthodox seeds or close to orthodox seed properties. Meanwhile, *C. javanica, H. crepitans*, and *S. foetida* are considered to have orthodox probably seed storage behaviour, indicating that these seeds are likely orthodox, but this has not yet been confirmed with certainty.

The seed storage behaviour of *C. grandis* is classified as orthodox. Its seed viability can be maintained for more than 3 years when stored in airtight containers at room temperature with a moisture content of 13±2% (SID 2025e). According to do Nascimento et al. (2021), *C. grandis* seeds exhibit physical dormancy, requiring pre-sowing treatments such as mechanical or chemical scarification before sowing in order to achieve high germination rates.

Based on Table 2, it can be seen that seeds with very short seed longevity with a decreasing rate of >30% are shown in *H. crepitans*, *I. miquelii*, *P. diversifolium*, *S. glutinosa*, and *S. foetida* seeds. Meanwhile, *C. javanica* and *C. scabra* seeds are categorized as seeds with short seed longevity (decreasing rate of 15-30%). *Cassia grandis* seeds have medium longevity with a decreasing rate ranging from 4-15%. The seed species with long longevity is *A. moluccana* because its decreasing rate is <5%.

Monitoring the viability percentage and cut-test of selected seeds after storage

Based on Figure 3.A, high seed viabilities (>85%) are found in *S. foetida*, *C. javanica*, and *C. grandis* seeds. In contrast, *S. glutinosa* seeds, which had been stored for approximately 7 years, cause a complete loss of viability (0%). This finding is supported by the cut-test results (Figure 3.B), which revealed that 100% of the seeds were empty at the end of the germination observation period. The large number of empty seeds indicates that the quality of *S. glutinosa* seeds was poor or that they had lost viability due to storage conditions that were incompatible with their storage behaviour. When seeds are stored under environmental conditions that do not match their storage requirements, they will be damaged and leading to a complete loss of viability. Empty seeds lack embryos and internal integuments such as testa and tegmen, and are therefore classified as non-viable (Huayta-Hinojosa et al. 2025). In addition to *S. glutinosa*, Figure 3.B also shows that empty seeds were found in *I. miquelii* and *P. diversifolium*, suggesting that these seeds may also be of low quality. Based on the cutting test results, *C. scabra, C. javanica, C. grandis*, and *A. moluccana* still have fresh seeds that have not germinated. This may suggest that the seeds need more time or specific environmental conditions to germinate, may be in a dormant state, or may require pre-treatment to stimulate germination.

The cut-test results of the selected seeds after approximately 7 years of storage in the seed banks showed that the embryos and endosperms of most seeds were still white and in fresh condition, except for *C. scabra* seeds, whose embryos and endosperms were relatively smaller in size compared to other selected species (Figure 4). The endosperm of *H. crepitans* was slightly darker, while that of *P. diversifolium* exhibited a unique wavy pattern. However, both remained in fresh condition. Dairel and Fidelis (2020) said that viable seeds are characterized by their health, potential for germination, and the presence of a healthy, milky-white, and fully developed embryo. Seed viability can be assessed using the cut test or the tetrazolium test.

Table 2. Decreasing rate and seed longevity of selected seed species after storage based on germination percentage monitoring

Scientific name	**Germination percentage (%)**		**(A - B) ± Stdev**	**Decreasing rate**	**Seed longevity**
	Initial (A)	**After storage (B)**			
Aleurites moluccana	0	0	0 ± 0	<5%	Long
Cassia grandis	10	0	10 ± 0	4-15%	Medium
Cassia javanica	25	1.33	23.67 ± 2.31	15-30%	Short
Colona scabra	23.33	2.67	20.66 ± 4.62	15-30%	Short
Hura crepitans	100	50.7	49.3 ± 8.33	>30%	Very short
Ixora miquelii	80	34.7	45.3 ± 16.7	>30%	Very short
Pterospermum diversifolium	100	49.3	50.7 ± 6.11	>30%	Very short
Swinglea glutinosa	100	0	100 ± 0	>30%	Very short
Sterculia foetida	100	66.7	33.3	>30%	Very short

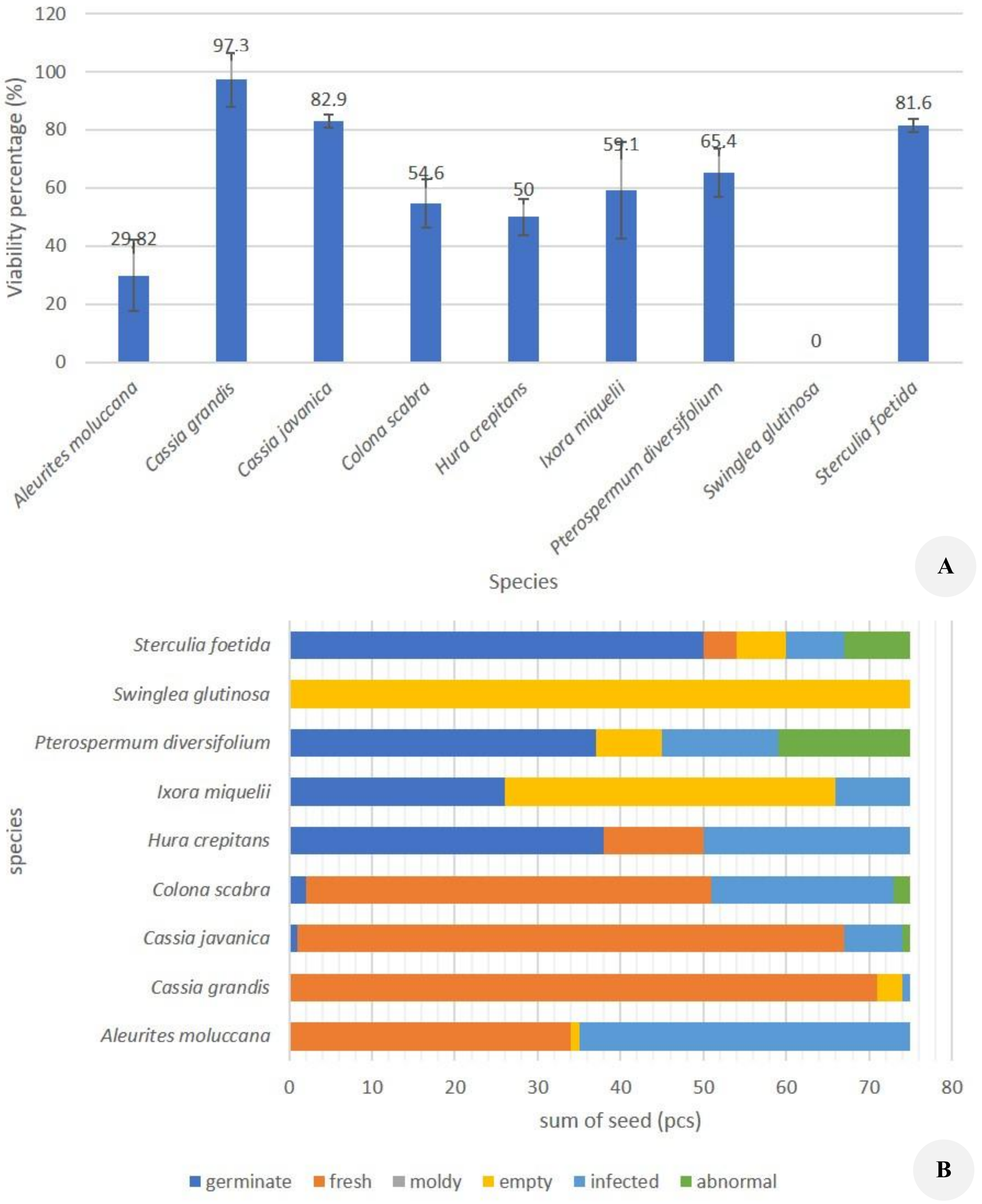

Figure 3. Monitoring viability results after storage: A. Seed viability of selected seed species after storage. Error bars represent mean ± standard deviation, and B. Sum of seed based on the cut-test result of selected seed species after germination test

SWOT analysis of monitoring the viability and longevity of selected seeds after storage to formulate a seed bank conservation strategy at PBG

The seed bank's conservation strategy at PBG, based on the analysis results of monitoring the viability and longevity of selected seeds after storage, is presented through the SWOT analysis (Table 3). The appropriate conservation strategy for the PBG Seed Bank is assertive or proactive, as the Strengths (S) and Opportunities (O) dominate the SWOT matrix (Figure 5). This leads to the formulation of an aggressive strategy for seed bank conservation at PBG, which includes the following actions: (i) Maximizing the use of existing seed bank equipment to enhance long-term seed storage capacity; (ii) Optimizing human resources, particularly competent seed researchers, and further improving their competencies through specialized training or workshops; (iii) Strengthening PBG's role as an ex-situ conservation area that produces quality seed materials; (iv) Developing innovative seed storage methods that align with the latest scientific advancements, (v) Utilizing seed diversity as a learning or educational attraction for academics and the wider public, (vi) Increasing routine seed viability monitoring and integrated monitoring data documentation.

Table 3. Internal factors (strengths and weaknesses) and external factors (opportunities and threats) of the seed banks at Purwodadi Botanic Garden, Indonesia

Internal factors	**Weights**	**Rating**	**Score**
Strengths (S)			
Purwodadi Botanic Garden has a documented seed bank collection	0.2	4	0.8
Adequate seed bank storage facilities	0.17	4	0.67
The seed bank collection stores mostly orthodox seeds	0.2	4.5	0.9
Adequate seed moisture measurement facilities	0.13	3.5	0.47
Adequate seed germination testing facilities	0.17	4	0.67
A sufficient number of competent seed biology researchers who understand seed conservation standards	0.13	3.5	0.46
Total S	1		3.97
Weaknesses (W)			
There is no specific seed drying room available	0.38	3	1.13
There are no technicians or researchers who can monitor seed germination after storage for a specific period	0.38	3	1.13
Information and determination of seed storage behaviours are still limited	0.25	2.5	0.63
Total W	1		2.88
External factors			
Opportunities (O)			
Further research is available on the results of seed viability monitoring after storage	0.37	5	1.87
Seed viability monitoring data is well-documented	0.37	4.5	1.68
The quantity and quality of seeds stored in the seed banks are adequate	0.25	4	1
Total O	1		4.56
Threats (T)			
Unstable electrical current in the seed storage room	0.21	3	0.63
Fluctuating temperature and humidity in the storage room	0.26	4	1.05
Appearance of mold or other microorganisms during seed storage	0.21	3	0.63
Damage to seed storage equipment or facilities	0.31	3	0.94
Total T	1		3.26

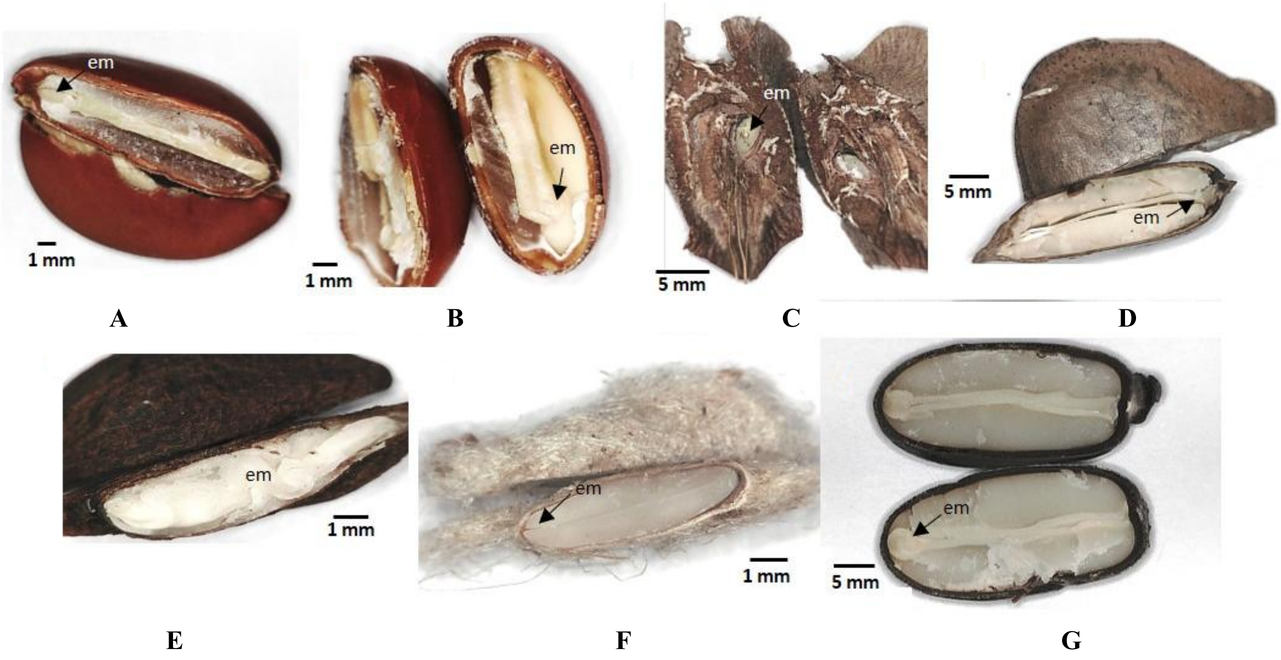

Figure 4. Cut-test result of selected seed species after storage using Dinolite microscope digital. A. *Cassia grandis,* B. *Cassia javanica,* C. *Colona scabra,* D. *Hura crepitans,* E. *Pterospermum diversifolium,* F. *Swinglea glutinosa* and G. *Sterculia foetida.* Note: em: Embryo

Figure 5. SWOT analysis to formulate the conservation strategy of selected seed species in Purwodadi Botanic Garden, Indonesia

Discussion

The findings of this research indicate that seed storage is closely linked to seed storage behaviour. Understanding a seed's storage behaviour enables the development of appropriate and efficient storage protocols that help maintain viability throughout the storage period. Understanding seed storage behaviour is essential before storing seeds, as misclassification can adversely affect seed longevity. The absence of information regarding the storage behaviour of *C. scabra*, *I. miquelii*, and *P. diversifolium* likely contributed to their marked viability loss, with each species exhibiting a high rate of decline (>30%). Seed storage behaviour is associated with the seed's tolerance to desiccation or drying (Trusiak et al. 2023). Therefore, seed storage conditions should be adjusted according to seed storage behaviour (Hong et al. 1996) to maintain seed viability during storage (de Vitis et al. 2020).

Besides determining the seed storage behaviour before storage, the initial condition of the seeds also plays a crucial role in maintaining seed viability during storage. Based on the results of the cut-test conducted before sowing, the condition of the embryo and endosperm in all tested species indicated that the seeds were filled and intact. The color of the embryo and endosperm was generally white, with no discoloration observed even after being stored for 7 years. Seeds are considered healthy when their internal structures, specifically the endosperm and embryo, are well-developed, filled, solid, and typically white or green in colour. Seed filling refers to the proportion of seeds that appear undamaged and contain all the essential tissues required for germination, namely an intact endosperm and embryo (Huayta-Hinojosa et al. 2025). Filled seeds generally indicate viability; however, viable seeds are not always guaranteed to be filled. Therefore, seed viability cannot be determined solely based on seed filling. Seeds from the Rutaceae family, such as *S. glutinosa*, typically exhibit low viability and low seed production. In addition, the storage behaviour of Rutaceae species remains largely unknown, hindering the development of appropriate storage protocols and further research on their germination and dormancy (Martyn et al. 2009).

Periodic monitoring of seed viability aims to predict seed longevity and facilitate further evaluation of seeds stored in the seed banks. Seeds with high longevity will be monitored periodically over a longer interval (every 10 years), while seeds with short longevity will undergo regeneration efforts to maintain their genetic diversity so that it remains available for further research or conservation purposes (Pratiwi et al. 2022). According to Hay and Whitehouse (2017), seed viability monitoring is a critical aspect of seed quality control for seed banks. In addition to genetic diversity data, viability monitoring also provides valuable information on the relative storage period of seeds.

Periodic seed viability monitoring by the Millennium Seed Bank (MSB) is conducted through germination tests every 10 years on orthodox seeds stored in cold storage. This monitoring aims to assess the longevity and viability of seeds preserved in the seed bank. Monitoring seeds stored in the seed bank is crucial for genetic plant conservation, as it confirms the effectiveness of storage conditions, helps predict seed longevity, tracks the health of collected seeds to maintain genetic diversity and seed integrity, and ensures seed availability for research, restoration, and sustainable use (Breman et al. 2021; Wambugu et al. 2023). Besides that, the function of a seed bank is not only to preserve species' genetic diversity but also to provide information about seed biology, seed physiology, seed germination ecology, plant adaptation, and evolution (Mattana et al. 2025). In conclusion, periodic monitoring of seeds in a seed bank is essential for making informed decisions regarding the seeds' history and aging, including whether they should continue to be stored or be regenerated (Balasupramaniyam et al. 2025).

SWOT analysis involves systematically identifying different factors to develop a strategy. It operates on the principle of enhancing strengths and opportunities while reducing weaknesses and threats. This method offers a structured framework for discussion and information exchange, helping to enhance strategic decision-making by management (Fadhillah et al. 2019). SWOT analysis for decision-making recommendations related to conservation strategies for plants conserved both ex-situ and in-situ has been widely carried out, but SWOT analysis for conservation strategies in seed banks has not been widely reported. The primary strategic priority identified from these SWOT analysis results is to enhance the competence and utilization of resources, including both seed bank technicians and seed storage equipment. Considering the role of PBG as an ex-situ conservation site that requires a backup collection in the form of a seed bank, this aligns with the seed bank's function as a complementary collection (Latifah et al. 2019). By maintaining a high-quality seed bank, various research and educational activities can be developed, benefiting the broader community, policymakers, and academics. To ensure the provision of quality seeds, accurate documentation and regular monitoring of seed viability are essential. Recommendations for conservation strategies of preserved plant collections also emphasize the importance of seed banks as a complement to living collection materials, as stated by Hapsari et al. (2024). The SWOT analysis for seed banks, especially at the Purwodadi Botanical Garden (PBG), can serve as a valuable reference or recommendation for relevant management stakeholders to ensure that ex-situ conservation strategies through seed banks are well-targeted, considering the numerous internal strengths and external opportunities identified. Based on the results of this research, it is expected that the proposed conservation strategies for the PBG Seed Bank can be implemented and further enhanced to ensure the preservation of genetic diversity in the form of seeds.

Regular monitoring of seed viability in seed banks, accompanied by a SWOT analysis, is essential as a recommendation for policymakers to support the provision of information related to seed characteristics. Seed characteristics determine seed aging. Information on seed characteristics is necessary in seed conservation efforts, including seed germination percentage, seed viability, and seed longevity. All observed seeds experienced a decrease in germination percentage. In general, this is not significantly different from other research, such as on *Schefflera abyssinica* seeds conducted by Bareke et al. (2022), in terms of the decrease in the ability of seeds to germinate after being stored for a certain time. Furthermore, Bareke et al. (2022) added that seed storage longevity was influenced by many factors such as seed maturation, pre-harvest handling methods, harvest time and weather conditions. As maintained by Pirredda et al. (2024), once stored, seeds would inevitably age and lose their viability over time, which establishes their longevity. Seed aging was a natural and permanent process that resulted in a gradual decline in seed quality. It first appears as a slow germination process, succeeded by a steady decline in viability shown by a rise in the percentage of seeds that cannot germinate, ultimately leading to the death of all seeds in the batch. In this study, the seed longevity of seeds stored for 7 years varied from very short, short, medium, to long longevity, with decreasing rates ranging from <5% to >30%. The condition of the embryo and endosperm in a still-viable seed does not always mean that the seed still has good germination ability, since according to Pirredda et al. (2024), seed longevity is regulated by a complex interaction between genetic factors and environmental conditions experienced during seed development and after maturation, which will shape seed physiology.

Supporting factors in seed conservation that are no less important are facilities from local seed banks and appropriate seed storage methods according to the characteristics of the seed species. Tiwari and Das (2014) believed that the use of appropriate storage resources with proper environmental exposure can maintain seed viability, resulting in better germination even after a long time. Tiwari and Das (2014) also maintained that recently, ascertained evidence showed that the choice of seed coating/treatment material, storage container, and storage environment had a positive result on seed viability and strength. Monitoring seed viability in seed banks plays a crucial role in the technical management and operation of these facilities. Bhattacharya and Mummenhof (2024) stated that to ensure the effectiveness of seed conservation programs, the viability of stored seeds needs to be assessed regularly and accurately. This is also supported by other researchers, i.e., Pradhan et al. (2022) who stated that seed viability testing, which was performed to assess whether seeds were still viable and usable after collection or after being in storage, was an important part of plant research and conservation; and Vivanco et al. (2021) who maintained that regular monitoring of the viability of seeds stored in germplasm banks is essential to determine when regeneration is necessary. The results of viability monitoring can inform decision-making related to conservation, particularly concerning seed longevity. Long-lived seeds are suitable for storage at low temperatures. Medium-lived seeds can also be stored at low temperatures but require more frequent monitoring, such as annually. Short-lived seeds should be preserved using alternative, more effective methods to maintain viability, such as cryopreservation, with monitoring conducted every 3 to 6 months. All stages of seed storage, from harvest to storage and viability monitoring, must adhere to the standards established by the International Seed Testing Association (ISTA) from the Royal Botanic Gardens, Kew. This research can serve as a reference for establishing new seed banks in Indonesia, where seed banks remain limited, currently including only the seed bank in Cibinong, West Java, and the seed bank at the Indonesian Botanic Gardens. This indicates that the variation in longevity among species depends on seed storage behaviour and the suitability of storage conditions according to internationally established standards.

Given the importance of seed viability monitoring in predicting seed aging and longevity, it is necessary to carry out viability monitoring on selected seed species that have been stored in seed banks for a certain period. These selected seed species are stored in seed banks at PBG as one of the ex-situ conservation areas. In addition to conserving living collections, PBG also preserves seeds collected from those living collections. According to Latifah et al. (2019), seed banks in botanic gardens serve three primary functions: as complementary collections (duplicates of the living plant collections in the botanic garden), supplementary collections (additional collections of species that have never been collected before), and active collections (seeds used for research, restoration, seed exchange, and other purposes). The seeds stored in the PBG Seed Bank have been maintained for more than five years. Therefore, seed viability monitoring is necessary to ensure that seeds from selected species in the PBG Seed Bank remain of sufficient quality for long-term storage.

In conclusion, seed storage behavior, seed characteristics, and storage conditions determine seed viability during storage, thereby affecting seed longevity. Recommendations from the SWOT analysis can serve as a basis for policymakers and seed bank management, particularly in PBG.

ACKNOWLEDGEMENTS

The authors would like to thank the Directorate of Talent Management, National Research and Innovation Agency (BRIN), Indonesia, for facilitating research assistance through Independent Learning Independent Campus (MBKM) students for the 2023/2024 period and the Directorate of Scientific Collection Management, BRIN, for permitting the use of seed material at the Purwodadi Botanic Garden Seed Bank, Pasuruan, East Java, Indonesia.

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