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Derivation of seed viability constants (K_E and C_W) and prediction of seed longevity for spider plant (*Cleome gynandra*)

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Abstract

Amid environmental challenges and the need for global food security, preserving and using plant genetic resources is vital. The expanded seed viability equation predicts longevity under varying storage conditions using species specific constants. While temperature-related constants (C_H and C_Q) are universally applicable across species, those related to seed moisture (C_W) and inherent longevity (K_E) vary by species and must be determined individually for accurate predictions. This study used spider plant (*Cleome gynandra*) to determine viability constants and establish seed longevity under genebank dry storage conditions. The seeds were subjected to experimental storage at 45°C and varied seed moisture contents (7.3, 11.7, 12.8, 14.2 and 15.3%) for 125 days to generate survival curves and hence, K_E and C_W: 7.656 and 3.55, respectively. The validation of these constants demonstrates their effectiveness in predicting seed longevity for other lots within the same species, showing no significant intraspecific variation. This study provides seed custodians and technologists with a reliable framework to accurately estimate the longevity of spider plant seeds under cold dry storage conditions using the viability equation and the constants derived herein.

Keywords: biodiversity preservation, genebank management, moisture content, opportunity crops, seed survival curve, seed viability, traditional vegetables, underutilised crops

Introduction

Spider plant (*Cleome gynandra* L.) is a versatile, nutritionally rich and highly adaptive species with the potential to address nutritional challenges (Molina *et al*., 2020). In an era marked by environmental uncertainties and the urgent need for sustainable food systems,

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the preservation and utilisation of such plant genetic resources have become critical (Volk *et al*., 2021). Despite its significance, the long-term viability and accessibility of spider plant genetic material remain complex and underexplored (Volk *et al*., 2023).

Seed viability, a fundamental parameter of seed quality, is directly linked to germination potential and longevity, which are critical for seed conservation and breeding programmes (Waterworth *et al*., 2019). Ensuring long-term viability is vital for sustaining ecosystems, supporting agriculture and preserving biodiversity (Reed *et al*., 2022; Teixidor-Toneu *et al*., 2023). Previous studies on spider plant have established basic storage guidelines such as optimal seed moisture content (5%) and suitable packaging materials like aluminum foil or polyethylene (Kamotho *et al*., 2013, 2014). These studies have primarily investigated short-term storage conditions. For instance, seeds harvested at the yellow pod maturity stage and dried to 5% moisture content maintained 85% germination during six months of room temperature storage (Kamotho *et al*., 2014). Additionally, spider plant seeds exhibit physiological dormancy, contributing to poor and irregular germination when sown immediately after harvest (Kamotho *et al*., 2013; Saifullah *et al*., 2023).

Predicting seed longevity requires a robust understanding of how environmental factors, particularly temperature and moisture content, influence seed ageing (Hay *et al*., 2022; Nadarajan *et al*., 2023). The expanded seed viability equation developed by Ellis and Roberts (1980) provides a mathematical framework for modelling seed longevity:

$$v = K_{\mathrm{i}} - p / 10^{K_{\mathrm{E}} - C_{\mathrm{W}} \log_{10} m - C_{\mathrm{H}} t - C_{\mathrm{Q}} t^2} \tag{1}$$

This equation incorporates four key constants: K_{E}, a species-specific constant for inherent seed longevity; C_{W}, another species-specific constant which quantifies the relative effect of change in seed moisture content (m) on seed longevity (σ); and C_{H} and C_{Q}, two constants that capture the influence of temperature on seed longevity and typically show insignificant variation across species (Dickie *et al*., 1990; Hay *et al*., 2022).

While the temperature constants (C_{H} and C_{Q}) are considered universal across species (Dickie *et al*., 1990), K_{E} and C_{W} for spider plant have not been published and this hinders evidence-based management of seed collections in genebanks. This study aimed to address this knowledge gap by deriving the viability constants K_{E} and C_{W} for spider plant seeds and establish seed longevity under dry storage genebank conditions.

Materials and methods

Seed samples

Based on the genebank seed viability data, three accessions were selected and used in this experiment (table 1). Seeds were sourced from Africa's Vegetable Genebank at the World Vegetable Center (WorldVeg) in Arusha, Tanzania, where they initially had 100% viability before storage. Prior to the experiment, viability was reassessed and only seed lots with germination above 85% were selected.

Table 1. *Cleome gynandra* accessions from the World Vegetable Center's Africa Vegetable Genebank, used in the seed longevity study.

Number	Accession name	Genebank code	Collection date	Country of Origin
1	GKK 285	RVI000858	21/07/2022	Malawi
2	IP 06	RVI000863	21/07/2022	Zambia
3	ML-SF-2	RVI000767	05/07/2022	Malawi

Adjustment of seed moisture contents

The longevity of spider plant accessions was determined by storing seeds at five different moisture content (MC) levels, 7.3, 11.7, 12.8, 14.2 and 15.3% (fresh-weight basis), at 45°C. Seed samples were humidified using non-saturated lithium chloride from the initial MC of 11.1% to the four higher MCs, while the lowest (7.3%) was achieved by drying over silica gel in a desiccator. During humidification, MCs were checked by frequent weighing and using the following formula (Demir *et al*., 2009):

$$\text{Seed weight at desired MC} = \text{initial weight} \times \frac{(100 - \text{initial MC})}{(100 - \text{desired MC})} \qquad (2)$$

The equilibrium moisture content (EqMC) was then estimated using enough intact seeds to fill a 3.2 ml sample holder measuring chamber of an AW-D10 water activity station used in conjunction with a HygroLab 3 display unit (Model: HygroLab 3, Rotronic AG, Bassersdorf, Switzerland). Measurements of water activity (aw = eRH/100) and temperature were recorded and converted to equilibrium moisture content (EqMC) using the Seed Information Database (SER/INSR/RBGK, 2025), which applies Cromarty's equation (IBPGR, 1990; Hay *et al*., 2022). The required seed oil content for *Cleome gynandra* (25.5%) was obtained from the same database. A similar approach was also applied by N'Danikou *et al*. (2024a).

Experimental storage

Accession GKK 285 was used for the determination of viability constants (K_E and C_W). For each moisture content, the sample was split into 10 subsamples of about 0.2 g, sealed inside labeled aluminum foil packets and placed in an incubator at 45°C. One packet per MC was removedafter 1, 2, 5, 9, 20, 30, 50, 75, 100 and 125 days and subjected to a germination test (Newton *et al*., 2014; Royal Botanic Gardens Kew, 2022).

Seed germination tests

Seeds were incubated in a germination chamber (Memmert IPP750 Plus, Memmert GmbH + Co. KG, Schwabach, Germany) to determine germination percentage using the top-of-paper (Petri dish) method as described by Rao *et al.* (2006). For each sampling period, a total of 200 seeds were used, distributed as 50 seeds per Petri dish across four replicates. Petri dishes were lined with filter paper, on top of which the seeds were placed, moistened with distilled water, and incubated in a controlled environment at a constant temperature of 30°C (Motsa *et al.*, 2015). Seeds were considered germinated when the radicle protruded at least 2 mm from the seed coat, following ISTA rules (ISTA, 2023). Germinated seeds were counted after 14 days and germination percentage (GP) calculated.

Modeling seed viability loss and determination of C_W and K_E

Seed longevity (life span) was estimated using the “viability metrics” package in R software (Aravind *et al.*, 2021), which evaluates multiple candidate models (probit, logit, Gompertz, Weibull) and selects the best-fitting model based on the lowest Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The selected model for this study was the probit model, which is internally implemented as a binomial generalised linear model, thereby fitting the Ellis and Roberts (1980) viability equation. The Ellis and Roberts (1980) viability equations were developed to make accurate predictions, from controlled storage experiments, of the probit viability (v) of a seed lot after a certain period of time (p) in air-dry storage, with K_i representing the initial probit viability:

$$v = K_i - p / \sigma \tag{3}$$

The slope is -1/ σ where σ is the time for viability to decline by one probit. The time taken for seed viability to fall from initial seed viability to 50% (p_{50}) was calculated as:

$$p_{50} = K_i \times \sigma \tag{4}$$

The effects of temperature (t), and moisture content (m), on seed longevity are species-specific, according to the equation:

$$\log_{10} \sigma = K_E - C_W \log_{10} m - C_H t - C_Q t^2 \tag{5}$$

Combining equations (4) and (5) produces the full viability model (equation 1):

$$v = K_i - p / 10^{K_E - C_W \log_{10} m - C_H t - C_Q t^2}$$

The relationship between the storage environment and seed longevity was quantified using linear regression, where log σ was plotted against log of moisture content (m), fitting the equation:

$$\log_{10} \sigma = K - C_W \log_{10} m \tag{6}$$

The value of K_E was calculated using the universal temperature coefficients of 0.0329 and 0.000478 for C_H and C_Q, respectively (Dickie *et al.*, 1990):

$$K_E = K + C_H t + C_Q t^2 \tag{7}$$

Subsequent plots and summaries were generated using ggplot2 and dplyr packages (Wickham, 2019; Wickham *et al.*, 2023). The slopes and intercepts were extracted from the model and used in the probit equations to derive species-specific viability constants.

Validation and application of the constants

Seeds from accessions ML-SF-2 and IP 06, produced under the same conditions as accession GKK 285, were used to validate the constants in a separate storage experiment, at 12.8% MC and 45°C. Seeds were taken from cold storage (5°C) and equilibrated to room temperature before opening and then adjusted to 12.8% MC using lithium chloride solution. Following equilibration, each sample was split into eight subsamples of 200 seeds, sealed inside aluminum foil packets then transferred to an incubator at 45°C. One packet was removed from the incubator after 0, 1, 2, 8, 14, 30, 50 and 75 days for germination testing. This schedule was modified from Newton *et al*. (2014) and Davies *et al*. (2016), and was selected to capture early- mid- and late-stages of viability decline. The observed viability loss for each of the accessions was compared with the predicted viability loss, estimated using the values determined for K_E and C_W (from accession GKK 285) together with the initial viability (K_i) for each of the accessions. Linear regression analysis was then conducted between the predicted and observed values to assess the validity of the determined constants. The derived C_W and K_E were also applied to predict seed longevity under medium- (5°C) and long-term (−18°C) genebank storage conditions.

Data analysis

Data analysis was conducted using R software (version 4.3.3; R Core Team, 2025) in RStudio (version 2025.05.0; RStudio Team, 2025). Germination percentage data were subjected to probit analysis (Equation 3) using the '*viability metrics*' package, specifically employing the '*FitSigma*' and '*FitSigma.batch*' functions as described by Aravind *et al.* (2021). *F*-tests were used to assess differences in seed survival curves, allowing comparison of both intercepts (initial viability) and slopes (rate of decline) among different seed moisture contents.

To test the assumption of linearity between the logarithm of the standard deviation of seed deaths (σ) and the logarithm of seed moisture content (MC), simple linear regression model was compared with a split-line regression model. The breakpoint in the split-line model represents the upper critical limit of the linear relationship between $\log_{10}(\sigma)$ and $\log_{10}(\mathrm{MC})$. Data points above this breakpoint were excluded from the estimation of viability constants (K_E and C_W) to avoid bias caused by deviation from linearity.

Results

Seed longevity decreased as moisture content increased, with a sharper decline observed at higher moisture levels (figure 1). *F*-tests applied to the full survival-curve fits revealed significant differences in intercepts (K_i) among moisture treatments ($F = 7.99$, $p < 0.001$). Seed longevity, as measured by p_{50}, declined with increasing moisture content, from 101 days at 7.3% moisture content to just eight days at 15.3% moisture content (table 2). A strong negative linear relationship was observed between $\log_{10}(\sigma)$ and $\log_{10}(\mathrm{MC})$ ($R^2 = 0.967$, $p = 0.0026$; figure 2). However, comparison with a split-line regression model indicated a significantly better fit ($R^2 = 0.997$), with a breakpoint at $\log_{10}(\mathrm{MC}) \approx 1.11$, corresponding to approximately 12.8% seed moisture content. Below this threshold, $\log_{10}(\sigma)$ declined linearly with increasing $\log_{10}(\mathrm{MC})$, while above the threshold the relationship was less steep.

Therefore, only values ≤ 12.8% MC were used in the estimation of K and C_W (equation 6). The estimated intercept (K) was 5.21 and the estimated slope (C_W) was 3.55. The derived K_E value (equation 7) for *Cleome gynandra* was 7.66, based on the universal values for C_H (0.0329) and C_Q (0.000478).

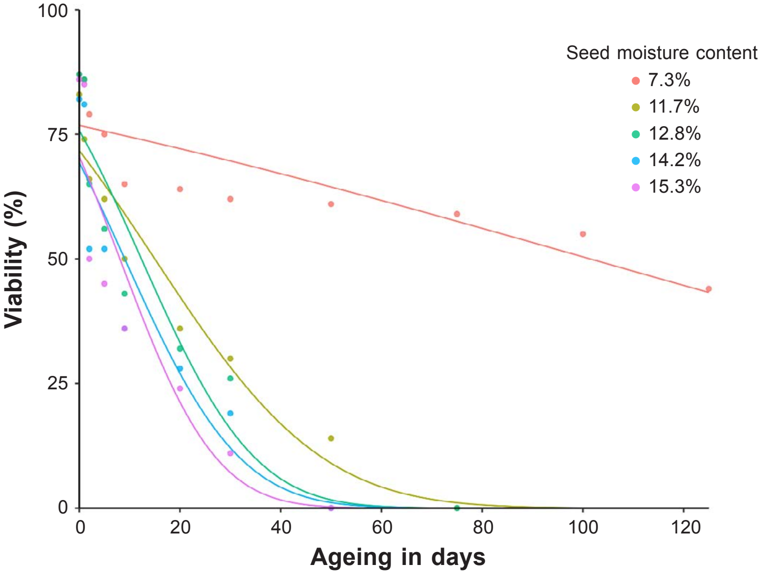

Figure 1. Survival curves of *Cleome gynandra* accession GKK 285 seeds at 7.3, 11.7, 12.8, 14.2 and 15.3% moisture content (fresh weight basis) and stored at 45°C.

Table 2. Parameters derived from the viability equation, illustrating changes in the germination ability of *Cleome gynandra* seeds of accession GKK 285 stored at 45°C.

Seed moisture content (% fresh weight)	eRH	K_i	1/σ ± SE	p_{50} (days)
7.3	36	0.73	-0.0072 ± 0.0013	101
11.7	72	0.58	-0.0384 ± 0.0040	15
12.8	78	0.70	-0.0566 ± 0.0060	12
14.2	86	0.51	-0.0559 ± 0.0064	9
15.3	90	0.54	-0.0669 ± 0.0076	8

eRH = equilibrium relative humidity, determined using an AW-D10 water activity station (Rotronic AG, Switzerland); K_i = initial probit viability of the seeds at the beginning of storage; 1/σ = the reciprocal of the standard deviation of seed survival time, reflecting the rate of viability loss; p_{50} = length of time for seed viability to decline to 50%.

Validation of the derived seed viability constants for Cleome gynandra

Using the derived constants, seed germination was predicted for seeds of accessions IP 06 and ML-SF-2 stored at 12.8% MC and 45°C. The predicted germination was higher than the observed germination, for both IP 06 and ML-SF-2 accessions (figure 3).

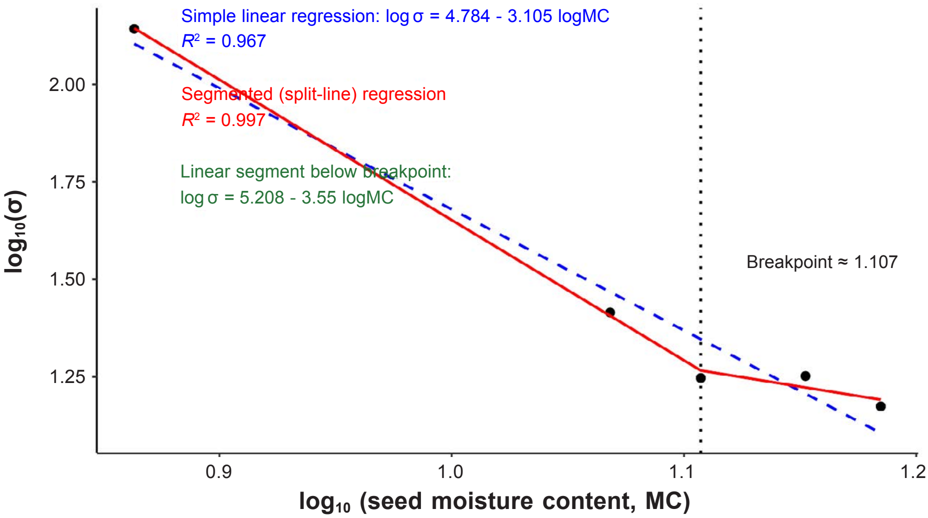

Figure 2. Linear and split-line relationships between $\log_{10}(\sigma)$ and $\log_{10}$ (moisture content – fresh weight) of *Cleome gynandra* accession GKK 285 seeds.

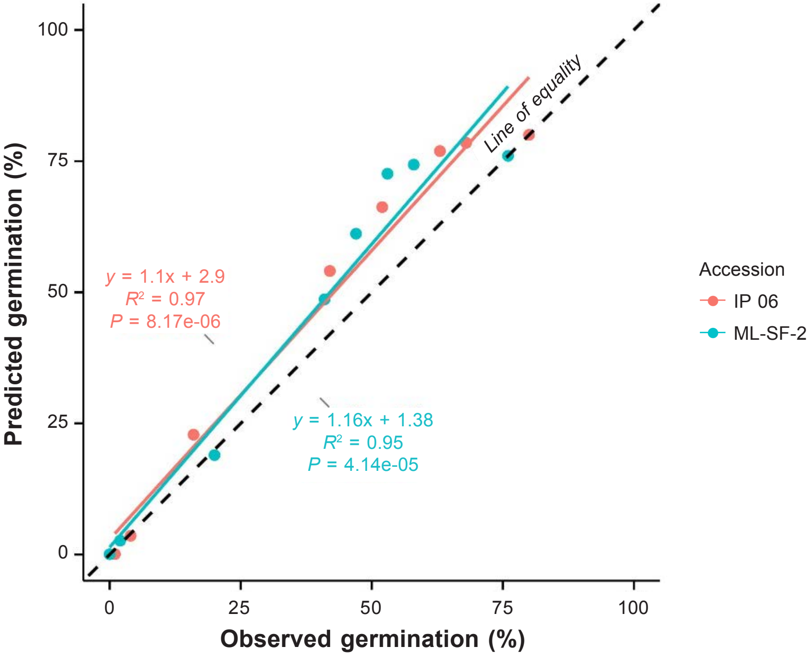

Figure 3. Observed versus predicted germination (%) for two *Cleome gynandra* accessions (IP 06 and ML-SF-2) during ageing at 45°C and 12.8% moisture content fitted by linear regression (solid lines). The dashed line is the line of equality (y = x) showing agreement between observed and predicted values.

Prediction of Cleome gynandra seed longevity under genebank storage conditions 5°C and −18°C

Applying the Ellis and Roberts (1980) viability equation to spider plant seeds with our parameter estimates indicated that storage at 5°C and 7% seed moisture would maintain viability above the 85% viability threshold for about 85 years (table 3). However, further lowering moisture content to 4% and reducing storage temperature to −18°C (the standard for long-term conservation) extended the predicted lifespan substantially to 2,518.7 years.

Table 3. Predicted seed longevity (time for viability to reach 85%; p_{85}) of *Cleome gynandra* stored at 5°C and −18°C.

Initial viability (%) prior to storage	Seed moisture content (% fresh weight)	Storage temperature (°C)	p_{85} (years)
98	7	5	85
98	7	−18	345.5
98	4	5	612.9
98	4	−18	2518.7

Discussion

Understanding seed ageing is essential for managing seed collections preserved in ex situ genebanks (N'Danikou *et al*., 2024b). The ageing pattern observed in *Cleome gynandra* aligns with the survival behaviour typical of orthodox seeds. Although intercepts (K_i) differed significantly among moisture treatments, the overall pattern of seed longevity appears to reflect broadly comparable initial quality of the seed lot. Storage conditions significantly influence seed deterioration rates and the shape of survival curves. Orthodox seeds exhibit longer longevity (higher p_{50}) at lower moisture content, with higher moisture levels accelerating deterioration due to metabolic activities like lipid peroxidation and protein carbonylation (Veselova *et al*., 2015). Accordingly, this study revealed a negative relationship between seed longevity and seed moisture content underscoring the fact that drying seeds to low moisture content is crucial before storage in the genebank.

This study estimated viability constants $K_E = 7.66$ and $C_W = 3.55$ for *Cleome gynandra* seeds, based on seed survival curves across a moisture content range of 7.3 to 12.8% and at an ageing temperature of 45°C. The strong fit of the data to the viability equations in this study ($R^2 = 0.997$) further supports the reliability of the derived constants for interpreting seed viability trends in *Cleome gynandra*.

This is the first study to estimate viability constants for a *Cleome* species, core members of the Cleomaceae family, and can serve as a reference. The Cleomaceae family shares a close evolutionary relationship with members of the Brassicaceae family, as supported by molecular phylogenetic analyses and biochemical traits (Mabry *et al*., 2020). Notably, *Cleome gynandra* is phylogenetically close to certain Brassicaceae crops (Edger *et al*., 2018; Hoang *et al*., 2023). The viability constants reported in this study fall within the range reported for some Brassicaceae members. For example, *Raphanus sativus* (radish) seeds were reported to have $K_E = 6.54$ and $C_W = 3.22$ (Coronado *et al.*, 2023), while *Brassica juncea* and *B. napus* have $K_E = 7.77$, $C_W = 4.56$ and $K_E = 7.72$, $C_W = 4.54$, respectively (Ellis *et al*., 1989).

International genebank guidelines recommend drying orthodox seeds to about 5% moisture and storing them at −18°C to ensure long-term conservation (FAO/IPGRI, 2014). Empirical evidence, such as the work of Hay *et al.* (2021), confirms that applying these conditions can dramatically extend seed lifespan, validating both the theoretical models and the practical guidelines. However, predicting seed longevity using the viability equation carries the risk of mis-estimation due to potential variability within species (N'Danikou *et al*., 2024a). Validating the derived viability constants (C_W and K_E) supports their reliability for predicting seed longevity across different seed lots within the same species, showing no significant intraspecific variation in seed longevity. These constants can help genebank managers and seed technologists in managing stored seed collections of *Cleome gynandra*, supporting germplasm regeneration planning and adherence to genebank standards (Daniel *et al*., 2012; N'Danikou *et al*., 2024b).

Conclusion and recommendation

This study enhances our understanding of seed longevity in *Cleome gynandra*. The derived constants offer valuable insights for the informed management of the species seed collections in genebanks. This is a further step in generating science-based information to improve standards of genebanks managing collections of lesser-known or underutilized crop species. Further research on the seed longevity in other crops is still required, as this information remains crucial for the effective seed management in genebanks.

Data availability

The datasets used and/or analysed during this study are available from the corresponding author on reasonable request.

Authors' contributions

Conceptualisation, S.N., B.S.K. and A.J.S.; methodology, B.S.K., A.J.S and S.N.; validation, S.N.; resources, S.N. and M.v.Z; data collection and curation, B.S.K., and A.J.S; formal analysis, B.S.K., A.J.S. and S.N.; writing—original draft preparation, B.S.K. and S.N.; writing—review and editing, S.N., A.J.S., H.S., M.S.K., W.H., G.M.T and M.v.Z; supervision, S.N. and G.M.T; project administration, S.N.; funding acquisition, S.N and M.v.Z. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

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