Seed Science Research

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Development of a predictive model for vigour loss in soybean seed

María Rita Gonzalez[1], Juan Alberto Arguello[2] and Diego Batlla[3]

[1]Grupo El Azul, Laboratorio SEA Calidad and Semillas, Tucumán, Argentina; [2]Escuela para graduados, Universidad Nacional de Cordoba Facultad de Ciencias Agropecuarias, Córdoba, Argentina and [3]Cátedra de Cultivos Industriales, Departamento de Producción Vegetal/Instituto de Investigaciones Fisiológicas y Ecológicas Vinculadas a la Agricultura (IFEVA), Facultad de Agronomia, Universidad de Buenos Aires, Ciudad Autónoma de Buenos Aires, Argentina

Research Paper

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Corresponding author: Diego Batlla; Email: batlla@agro.uba.ar

Abstract

Maintaining high vigour values during post-harvest storage is a key goal for the seed industry, since high-vigour seeds ensure proper crop establishment under different agroclimatic conditions. The objective of this study was to evaluate the effect of seed moisture, storage temperature, initial vigour and damage on vigour loss in soybean seeds and to develop a model to predict this process based on the evaluated variables. For this purpose, soybean lots with different moisture and vigour levels were obtained by accelerated ageing (AAT) at harvest. Seeds were hermetically stored at 15°C and 25°C for seven months, and vigour was assessed at regular intervals using AAT (72 h at 41°C). The dynamics of vigour loss were fitted to a negative cumulative normal distribution function, and the obtained parameters (P_{V50} and σ) were related through regressions to initial quality and storage conditions. The model accurately predicted vigour loss in most cases. The results allowed quantification of the impact of each factor and simulation of scenarios to improve management and maintain vigour during storage. This provides a useful tool to optimize decisions regarding storage, monitoring and marketing of soybean seeds.

Introduction

The growing global demand for food, combined with the impacts of climate change on agricultural production, is placing increasing demands on seed quality to ensure successful crop establishment. In this context, the use of high-vigour seeds enhances establishment success by enabling crops to better adapt to a wide range of environmental conditions (Finch-Savage and Bassel, 2016; Powell, 2022). Vigour assessment is a key component of the seed industry, as it enables monitoring of the physiological potential of seed lots throughout the production process and supports informed management decisions (Marcos-Filho, 2015b). Nevertheless, despite its importance, information on seed vigour remains scarce compared with data on viability, and research into its dynamics during storage and its relationship with longevity is still limited.

Seed vigour, defined by ISTA (2022) as 'the sum of those properties that determine the activity and performance of seed lots, of acceptable germination, over a wide range of environments', is a complex trait that reflects multiple aspects of seed physiological potential. Unlike the standard germination test (G), vigour tests provide a more precise and sensitive measure of physiological deterioration, enabling early detection of ageing symptoms (Ellis and Roberts, 1981). This makes them valuable tools for predicting seed lot performance during storage and under field conditions (TeKrony and Egli, 1977; Marcos-Filho, 2015a). Among these, accelerated ageing (AAT) and tetrazolium (Tz) tests play a central role in soybean (*Glycine max*) seed quality assessment (Marcos-Filho, 2015a; França-Neto and Krzyzanowski, 2022), as storage-related deterioration is typically expressed as a progressive decline in seed performance potential (Marcos-Filho, 2015a).

Soybean seeds, due to their morphological and physiological characteristics, are particularly susceptible to deterioration and vigour loss during storage, as well as to damage during harvest and processing (Parrish and Leopold, 1978; Marcos-Filho, 2015a). This vulnerability is exacerbated under unfavourable environmental conditions, such as those in tropical and subtropical regions, where maintaining physiological quality is especially challenging. Numerous studies have documented the effects of storage temperature and seed moisture content on soybean seed viability and vigour, showing that increases in either factor reduce storage lifespan (Smaniotto et al., 2013; Carvalho et al., 2014; Marcos-Filho, 2015a; Ferreira et al., 2017). High initial physiological quality is associated with slower deterioration rates during storage (Marcos-Filho, 2015a), whereas environmental and seed coat damage reduce physiological quality and compromise vigour preservation (TeKrony et al., 1980; De Souza and Marcos-Filho, 2001;

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Moreano et al., 2011; Forti et al., 2013; Torres Licursi Vieira et al., 2013; Teixeira et al., 2024; Barrionuevo et al., 2025). However, despite these insights, the practical application of such findings in the production sector remains limited (Marcos-Filho, 2015a).

The interaction of three key factors – seed moisture, storage temperature and initial quality – ultimately determines seed quality at the end of the storage period (Bewley et al., 2013). Ellis and Roberts (1980, 1981) pioneered the quantitative description of this relationship through the viability equation, which models changes in the viability of orthodox seeds during storage. Their work demonstrated that viability declines follow a negative sigmoidal pattern, indicating that not all seeds die simultaneously (Ellis, 2022). Similarly, population-threshold models assume that seed populations exhibit underlying normal distributions in their responses to ageing (Bradford et al., 1993). Over the past decades, these models, or their derived parameters, have been applied to assess seed longevity across species and storage conditions (Hay et al., 2018, 2022), proving valuable for identifying species-specific storage characteristics and improving both commercial storage practices and germplasm conservation (Ellis, 1988). Although similar approaches could be used to predict the decline in seed vigour during post-harvest storage, such models have not been developed to date.

Many trials have been conducted to study how different storage conditions and seed quality parameters affect the loss of vigour in soybean seeds; however, there are no studies that have attempted to quantify the relative impact of each of these factors in real production systems. Such knowledge would be critical for identifying practices essential to producing high-quality seeds. Moreover, no predictive models have been developed to estimate the effects of these factors on vigour changes during storage. The ability to forecast vigour loss would allow seed companies to make strategic decisions to preserve quality, optimize lot management and improve operational efficiency throughout production and marketing.

In light of this knowledge gap, the objectives of this study were to:

a) quantify the effects of storage temperature, seed moisture content and initial vigour on vigour loss during storage of soybean seeds; and

b) develop a quantitative, population-based model to predict vigour loss in soybean seed lots under commercial storage conditions as a function of these variables.

Materials and methods

Biological material

Soybean (*Glycine max* (L.) Merrill) seeds of the cultivars 62R63 RSF (a glyphosate-tolerant genotype) and 67i70 RSF PRO (a glyphosate- and Cry1Ac lepidopteran-tolerant genotype) were used. Seeds were produced during the 2021/2022 and 2022/2023 growing seasons by the soybean seed production company Estancia El Azul S.A. (Puesto de Uncos, Tucumán Province, 26°27′S 64°40′W) and Estancia Los Mirkos S.A. (General Mosconi, Salta Province, 22°35′S 63°47′W).

Twenty-four commercial seed lots differing in vigour (assessed by the Accelerated Ageing Test, AAT; ISTA, 2022) and moisture content at harvest were selected. These lots were chosen to represent the range of variability typically encountered in commercial soybean seed production systems. Ten seed lots of cultivar 62R63 RSF were used for model development. Whereas the remaining 14 seed lots, produced in Tucumán (2022) and Salta (2023), were used for model validation. These lots represented independent datasets that differed in genotype, production environment and seed damage levels. At the time of sampling, seeds had been stored for 45 days in silo bags under field conditions.

Seed quality assessment

Immediately after sampling, initial seed quality was assessed using tests described below. Laboratory tests were conducted at the seed quality laboratory (Estancia El Azul S.A.), accredited by the Argentine National Seed Institute (INASE-Registration No. RNCyFS I-7073).

- Germination test (G)

Four replicates of 50 seeds were sown. Seeds were placed in sand moistened to 40% of its water-holding capacity in plastic trays (26 × 19 × 5 cm), enclosed in polyethene bags to maintain humidity and incubated at 25°C ± 2 under a 16 h dark/8 h light regime according to ISTA (2022). After six days, seedlings were evaluated according to the Handbook on Seedling Evaluation (ISTA, 2018), and results are expressed as percentages.

- Tetrazolium test (Tz)

Four replicates of 25 seeds were preconditioned between moist paper for 16 h at room temperature. Seeds were then immersed in a 0.1% aqueous solution of 2,3,5-triphenyltetrazolium chloride (pH 7) and incubated at 35°C for 3 h in darkness. Each seed was examined, and the mechanical, environmental and insect-related damage levels were determined following the Argentine National Agricultural Institute reference patterns (França-Neto and Krzyzanowski, 2022). Results are expressed as percentages.

- Accelerated ageing (AAT, 72 h)

Fungicide-treated seeds (42 g; pyraclostrobin 5% + thiophanate-methyl 45%, 100 ml/100 kg seed) were incubated at 41°C ± 0.3°C and 95% RH for 72 h following ISTA (2022). Afterwards, four replicates of 50 seeds were sown in sand moistened to 40% of its water-holding capacity and incubated under the same conditions as the germination test. Normal seedlings were counted after six days, and results are expressed as percentages.

- Moisture content (MC)

Seed moisture content was measured with a hygrometer (Delver, model HD1021USB, Buenos Aires, Argentina) calibrated for soybean, using the low-temperature oven method (17 h at 103°C; ISTA, 2022). Results are expressed on a wet basis (%).

- Thousand seed weight (TSW)

Determined by weighing 1000 pure seeds according to ISTA (2022). Results are expressed in grams.

- Seed coat cracking

Seed coat cracking was assessed following BASF's working protocol SQ-WI-02853 – QC – External Analysis – Soybean – AR. From the seed fraction retained on a 4.75 mm sieve, 100 g was weighed and damaged seeds were identified and separated. This damage was

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characterized by ruptures in the outer seed coat forming irregular cracks, usually perpendicular to the hilum. The fraction of damaged seeds was weighed, and results are expressed as percentages.

Experimental storage conditions

After the initial seed quality assessment, 200 g subsamples of each seed lot were placed in polyethene zipper bags (10 × 15 cm, 75 μ) sealed with cling film to prevent moisture loss and stored for six months at constant temperatures of 15°C ± 1°C or 25°C ± 1°C. During storage, bags were removed at regular intervals for AAT testing (ISTA, 2022). In the first year, tests were performed every two months; in the second year, every 20 days. Storage temperatures were monitored using a TPD8358 temperature datalogger (Lascar Electronic, USA). At the end of the storage period, seed weight was tested in selected samples, and no variation was detected compared with the initial weight, indicating that seed moisture was maintained throughout storage.

Modelling vigour loss

Seed vigour loss (quantified by AAT) during storage under different conditions of seed moisture, temperature and initial AAT was described using negative cumulative normal distribution curves, according to the following equation:

$$AAT_p = \Phi\left(\left(P_{V50} - P\right)/\sigma\right) * AAT_{in} \quad (1)$$

where:

- AAT_p = germination percentage after AAT at time p
- AAT_{in} = observed initial AAT for each seed lot
- $\Phi(x)$ = cumulative distribution function of the standard normal distribution
- P_{V50} = time required for AAT (i.e. germination) to decline to 50% of AAT_{in} (months)
- P = storage time (months)
- σ = standard deviation of the AAT decline distribution within the seed population (months)

Equation 1 was independently fitted to each seed lot and storage condition using the Generalized Reduced Gradient nonlinear optimization algorithm implemented in the Solver tool of Microsoft Excel. Model parameters (P_{V50} and σ) were estimated by minimizing the Root Mean Square Error. Parameters derived from the fitted curves (P_{V50} and σ) were subsequently used to develop predictive equations describing the effects of storage conditions and seed quality attributes on vigour loss.

Statistical analysis

Standard errors (SE) of the estimated P_{V50} and σ values were obtained using a non-linear least-squares (nls) algorithm. These parameters were then analysed by Weighted Least Squares multiple linear regression, with the reciprocal of their SE as the weighting factor, to evaluate the effect of the studied variables on soybean seed vigour. All two-way and three-way interactions among the explanatory variables (seed moisture content, storage temperature and initial seed quality parameters) were evaluated during model development. Regression coefficients were tested for significance using a t-test, and global model performance was compared using an F-test ($p < 0.05$). Analyses were performed with InfoStat software (Di Rienzo et al., 2020).

Results

All soybean seed lots had germination (G) above the Argentine commercial standard (>80%). Vigour (AAT_{in}) ranged from 68 to 94%, stink bug damage from 2 to 8%, mechanical damage from 6 to 15%, environmental damage from 15 to 28%, seed coat cracking from 4 to 31% and thousand-seed weight from 128.2 to 191.3 g, quality values typical of commercial seed lots in northwestern Argentina (Table 1).

Vigour loss during storage increased with seed moisture content and storage temperature (Figure 1). Lots with <13% moisture stored at 15°C maintained high vigour (>70%) for six months, whereas those with >13% moisture fell below this threshold within four months. At 25°C, vigour declined more sharply, particularly at higher moisture contents; only seeds at 10% moisture retained high vigour throughout storage. Initial vigour had little effect on vigour loss within the range evaluated (AAT > 68%), except in seeds with >13% moisture stored at 25°C. Changes in seed vigour during storage, as measured by AAT, were well described by fitting equation 1 (Figure 1). Coefficients of determination (R^2) ranged from 0.70 to 1.00 in 95% of cases (Table 1). The P_{V50} values obtained from curve fitting (equation 1) showed that the time required for vigour to decline to 50% of its initial level was inversely related to seed moisture content (ρ −0.57) and storage temperature (ρ −0.74).

Using the fitted parameters P_{V50} and σ, the seed population dynamics of vigour loss could be adequately described. Both were related to seed quality traits and storage conditions through multiple linear regression (Table 2). Analysis revealed significant negative associations between P_{V50} and storage conditions as well as seed damage (environmental, seed coat cracking, insect-related), with moisture content and storage temperature showing the strongest effects ($p < 0.0001$). In contrast, σ was significantly related only to seed moisture content, showing a linear relationship with a coefficient of determination ($R^2 = 0.51$). Although all two-way and three-way interactions were initially evaluated, none significantly improved model performance ($p > 0.05$). Therefore, the final predictive equations included only main effects. Seed moisture content was expressed as $\log_{10}$(MC), following the seed viability equation of Ellis and Roberts (1980), in which the effect of moisture content on seed longevity is described on a logarithmic scale. Storage temperature was retained in the final model considering its biological relevance and potential predictive value, despite its limited effect on σ within the evaluated range.

Based on multiple regression coefficients, two linear equations were developed to model P_{V50} and σ in relation to seed moisture content (MC), storage temperature (T), environmental damage (ED) and seed coat cracking (SCC):

$$P_{V50} = 54.14 - 33.64 * \log MC - 0.41 * T - 0.14 * ED - 0.05 * SCC \quad (2)$$

$$\sigma = 15.61 - 12.58 * \log MC - 0.02 * T \quad (3)$$

Parameters (P_{V50} and σ) estimated by multiple linear regression using Equations 2 and 3 were used in Equation 1 to predict vigour decline in soybean seed lots of cultivar 62R63 RSF produced in 2022. The results showed that vigour decline was accurately predicted for these seed lots, which were the same lots used for model development. ($R^2 = 0.85$–0.89; Figure 1B).

The model (equations 1–3) also adequately described vigour loss in seeds stored at different moisture levels at 15 and 25°C for two cultivars produced in the same year in Tucumán (Figures 2A, B

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Table 1 Initial quality parameters of soybean seed lots (62R63 RSF, 2022) assessed through seed moisture content (% wet basis), germination percentage (G), vigour by accelerated ageing (AAT), percentage of mechanical, environmental and stink bug damage determined by the Tetrazolium test, seed coat cracking and thousand-seed weight (TSW). Fitted values of P_{V50}, σ and R^2 derived from Equation 1 under storage at 15 and 25°C

Lot ID	Seed moisture content (%)	G (%)	AAT_{in} (%)	Mechanical damage (%)	Environmental damage (%)	Stink bug damage (%)	Seed coat cracking (%)	TSW (g)	Temperature storage (°C)	P_{V50} (months)	σ	R^2
L1	10.1	96	94	10	16	4	14	158.5	15	12.0	3.7	0.70
									25	8.0	2.3	0.81
L2	10.5	91	85	15	16	5	16	162.0	15	11.8	2.8	0.36
									25	7.0	2.0	0.93
L3	11.4	93	89	6	23	4	4	128.2	15	9.0	3.4	0.95
									25	4.8	2.1	0.98
L4	11.1	90	87	13	21	2	25	170.8	15	8.2	1.9	1.00
									25	4.4	2.0	0.98
L5	11.7	98	90	12	20	3	31	191.3	15	8.8	3.2	0.98
									25	3.2	1.7	1.00
L6	11.6	94	85	12	28	6	13	150.5	15	7.2	1.1	0.84
									25	4.0	2.6	0.89
L7	11.6	87	73	10	26	8	12	146.4	15	7.5	0.9	0.77
									25	3.0	1.5	0.99
L8	13.9	95	90	11	15	5	8	177.6	15	7.3	2.4	0.93
									25	2.8	0.9	1.00
L9	13.9	94	80	14	16	7	16	181.1	15	6.4	1.2	0.91
									25	2.1	1.1	1.00
L10	13.2	96	68	10	25	7	15	178.7	15	5.9	0.8	0.99
									25	1.7	0.4	1.00

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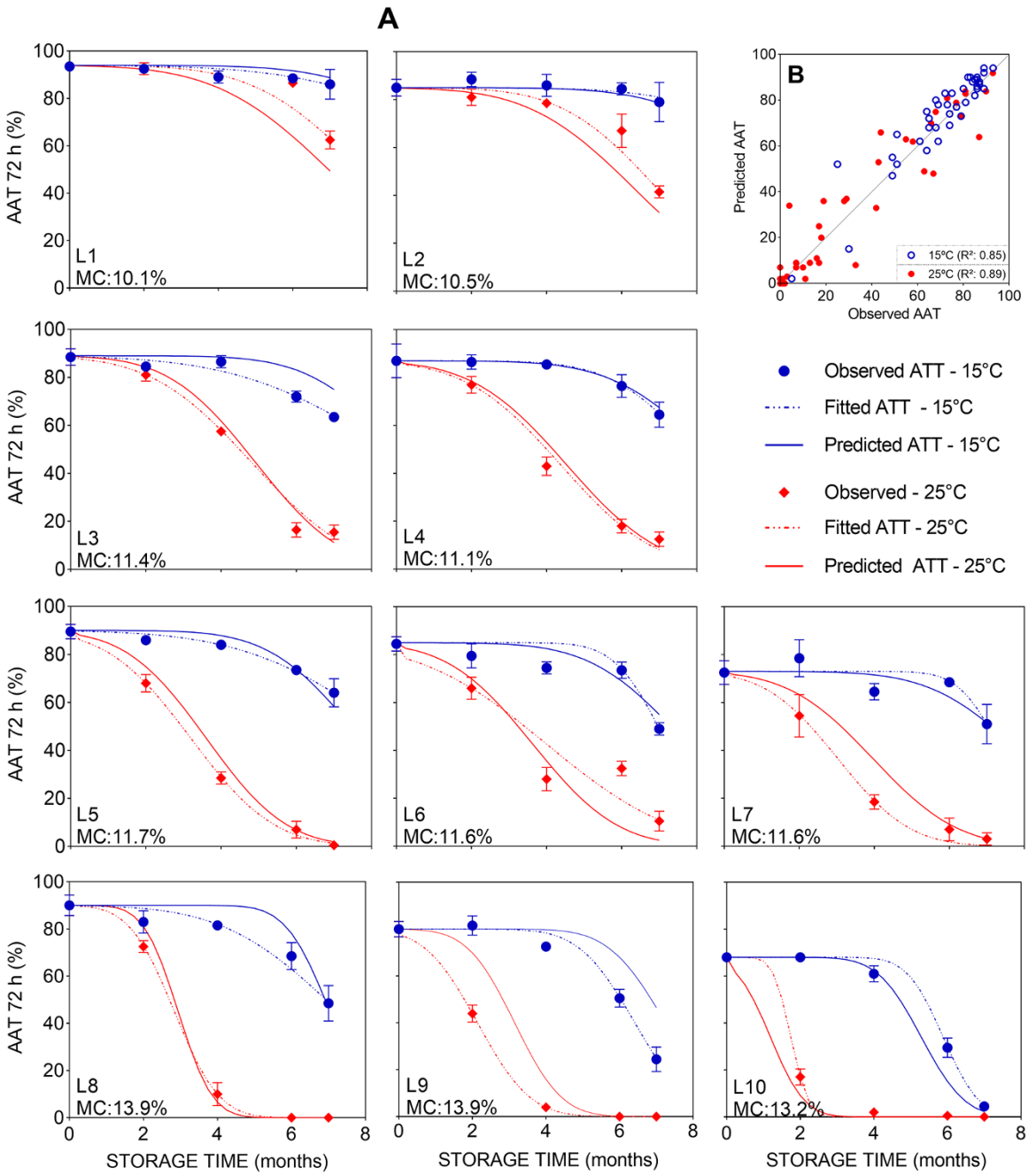


Figure 1. (A) Dynamics of vigour (AAT, 72 h) during storage of different lots of soybean seeds (L1–L10; 62R63 RSF, 2022) at different seed moisture contents (10.1–13.9%), storage temperatures (15°C, blue; 25°C, red) and initial vigour (high to low, left to right). Symbols represent observed data. Dashed lines represent AAT values fitted using an optimization procedure based on Eq. 1 and solid lines, values predicted by Eq. 1 using P_{V50} and σ estimated from Eqs. 2 and 3, respectively. (B) Relationship between observed and predicted AAT values under both storage temperatures.

Table 2 Multiple linear regressions for estimating P_{V50} and σ as a function of storage conditions and seed quality

	Coefficients						
Parameter	Intercept	Log moisture content	Temperature storage	Environmental damage	Seed coat cracking	R^2	AIC
P_{V50}	54.14 ± 4.19	−33.64 ± 2.67****	−0.41 ± 0.03****	−0.14 ± 0.02***	−0.05 ± 0.005*	0.95	85.81
σ	15.61 ± 1.37	−12.58 ± 1.09***	−0.02 ± 0.003	–	–	0.51	77.54

**** $p < 0.0001$; *** $0.0001 < p < 0.001$; * $p > 0.01$.

and Figure 3A, B; Table 3). In contrast, for seed lots produced in 2023 in Salta, which exhibited high levels of stink bug and seed coat cracking, the model was less accurate, overestimating vigour values (Figures 2C and 3C; Table 3).

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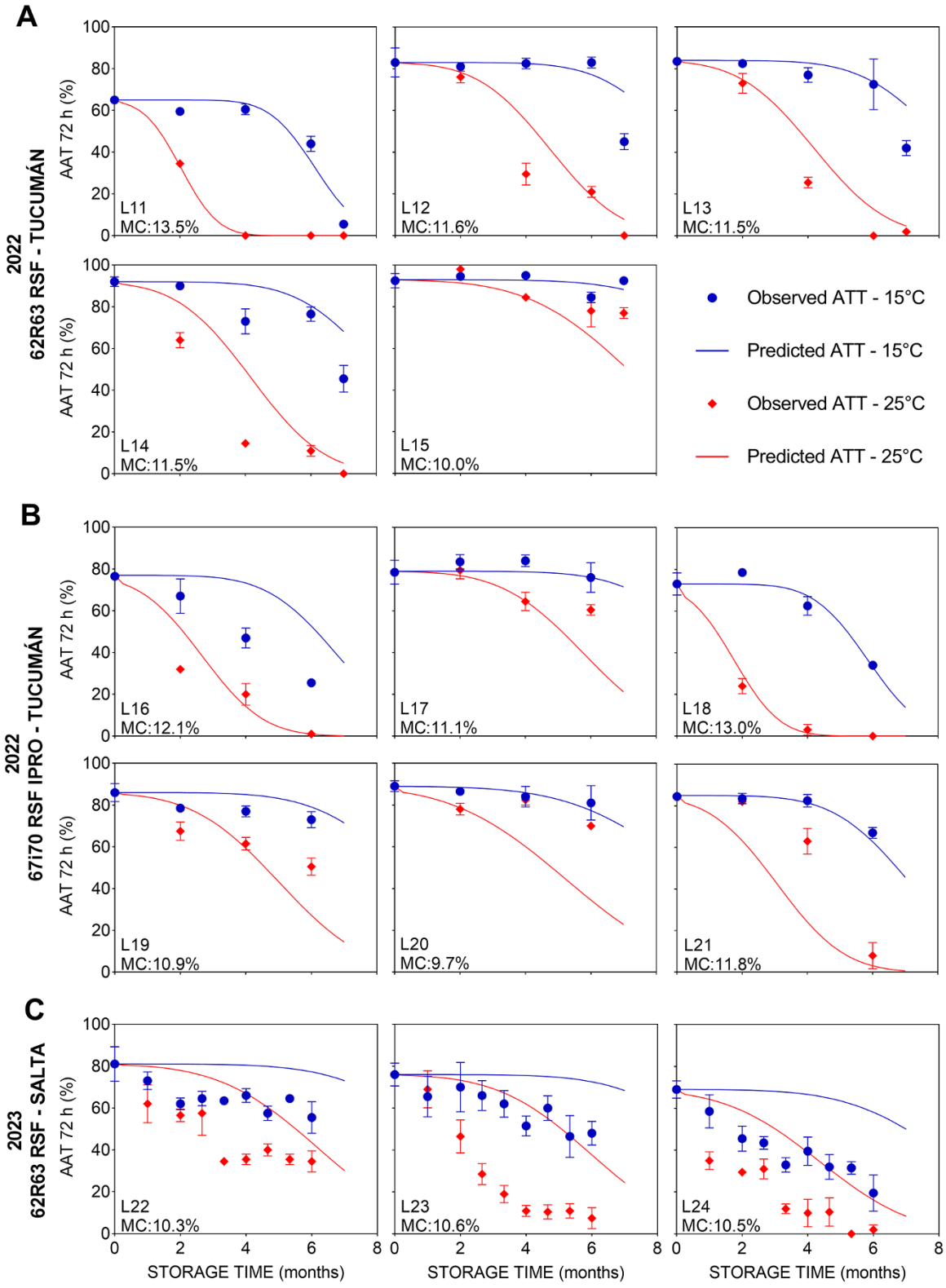


Figure 2. Dynamics of soybean seed vigour (AAT) during storage of independent soybean seed lots (L11–L24) at 15°C (blue) and 25°C (red). Symbols represent observed data and solid lines represent values predicted by Eq. 1 using P_{V50} and σ estimated from Eqs. 2 and 3, respectively. Panels show lots of cultivars: (A) 62R63 RSF, Tucumán 2022; (B) 67i70 RFS IPRO, Tucumán 2022; and (C) 62R63 RSF, Salta 2023.

Equation 2 was further used to simulate the effects of seed moisture content and storage temperature on P_{V50} values, fixing damage levels at low and high, to assess how storage conditions could be optimized to preserve lot vigour. For seed lots with low-damage levels (Figure 4A), greater flexibility was observed in selecting moisture and temperature conditions while maintaining vigour

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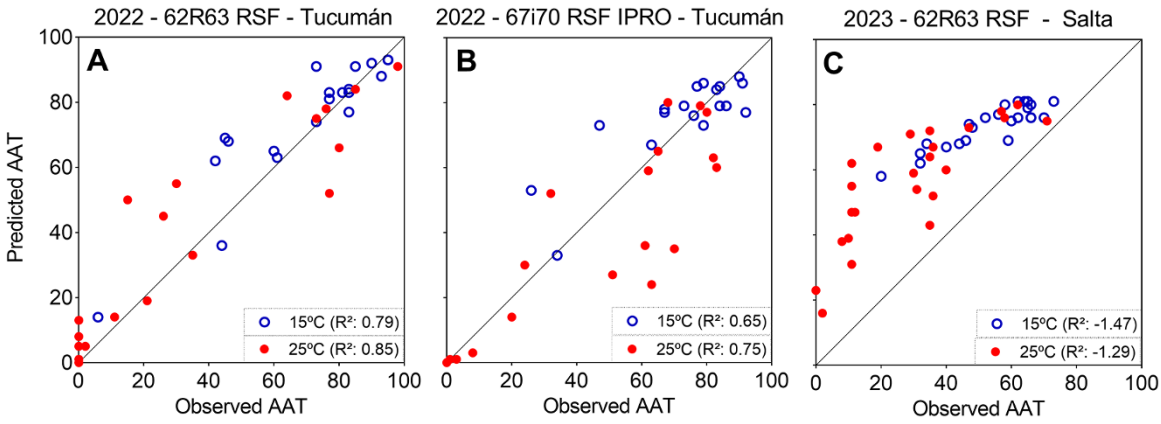


Figure 3. Relationship between observed and predicted AAT values for independent validation seed lots (L11–L24) stored at 15 and 25°C. (A) 62R63 RSF, Tucumán 2022; (B) 67i70 RFS IPRO, Tucumán 2022; and (C) 62R63 RSF, Salta 2023.

Table 3 Initial quality parameters of soybean seed lots (62R63 RSF and 67i70 RFS IPRO) produced in Tucumán (T) and Salta (S), 2022–2023. Assessed through seed moisture content (% wet basis), germination percentage (G), vigour by accelerated ageing (AAT), percentage of mechanical, environmental and stink bug damage determined by the Tetrazolium test, seed coat cracking and thousand-seed weight (TSW)

Lot ID	Year	Cultivar	Location	Moisture content seed (%)	G (%)	AAT_{in} (%)	Mechanical damage (%)	Environmental damage (%)	Stink bug damage (%)	Seed coat cracking (%)	TSW (g)
L11	2022	62R63 RSF	T	13.5	93	65	11	21	5	18	179.9
L12	2022	62R63 RSF	T	11.6	95	83	12	20	8	11	153.3
L13	2022	62R63 RSF	T	11.5	98	92	12	16	4	36	187.6
L14	2022	62R63 RSF	T	11.5	92	84	11	17	6	33	180.9
L15	2022	62R63 RSF	T	10.0	96	93	13	16	2	13	150.8
L16	2022	67i70 RSF IPRO	T	12.1	95	77	12	34	9	0	151.7
L17	2022	67i70 RSF IPRO	T	11.1	91	79	8	21	6	1	158.3
L18	2022	67i70 RSF IPRO	T	13.0	96	73	7	33	5	1	154.3
L19	2022	67i70 RSF IPRO	T	10.9	96	86	7	28	6	0	152.8
L20	2022	67i70 RSF IPRO	T	9.7	91	89	4	39	11	1	151.2
L21	2022	67i70 RSF IPRO	T	11.8	96	85	1	34	3	0	156.2
L22	2023	62R63 RSF	S	10.3	97	81	8	15	26	30	178.0
L23	2023	62R63 RSF	S	10.6	92	76	9	13	18	32	194.2
L24	2023	62R63 RSF	S	10.5	87	69	4	28	33	25	184.1

for longer periods (P_{V50} = 5–10 months). In contrast, for lots with high levels of environmental damage and seed coat cracking (Figure 4B), storage conditions needed to be strictly controlled at very low moisture and temperature levels to effectively preserve vigour.

Discussion

In this study, the quantitative effects of storage temperature, seed moisture content, initial seed vigour and damage levels on soybean seed vigour loss measured by AAT during storage were evaluated. As widely documented, soybean seed vigour declines more rapidly with increasing seed moisture and/or storage temperature (Ellis et al., 1982; Dickie et al., 1990; Marcos-Filho, 2015a; Ferreira et al., 2017), making these the most influential factors in this process (Figure 1). Another factor usually affecting the rate and extent of deterioration is the initial quality of the seed lot (Bewley et al., 2013; Marcos-Filho, 2015a; Ellis, 2022). However, in the present work, the effect of initial AAT vigour did not appear to significantly influence vigour loss dynamics. It is important to note that the AAT values used in this study were always higher than 68%, as values below this threshold lead to rejection at the industrial level. The use of seed lots with lower initial AAT values would likely have resulted in a significant effect of this factor.

Seed coat cracking and environmental damage were negatively correlated with vigour loss during storage (Table 2), consistent with previous studies showing that environmental damage and its progression affect soybean seed viability and vigour (Moreano et al., 2011; Forti et al., 2013). The negative impact of seed coat cracking may be related to disruptions in seed coat integrity, which reduce the physiological potential of the seed (De Souza and Marcos-Filho, 2001; Torres Licursi Vieira et al., 2013; Teixeira et al., 2024; Barrionuevo et al., 2025). Previous studies examined these effects in isolated cases but did not establish a quantitative

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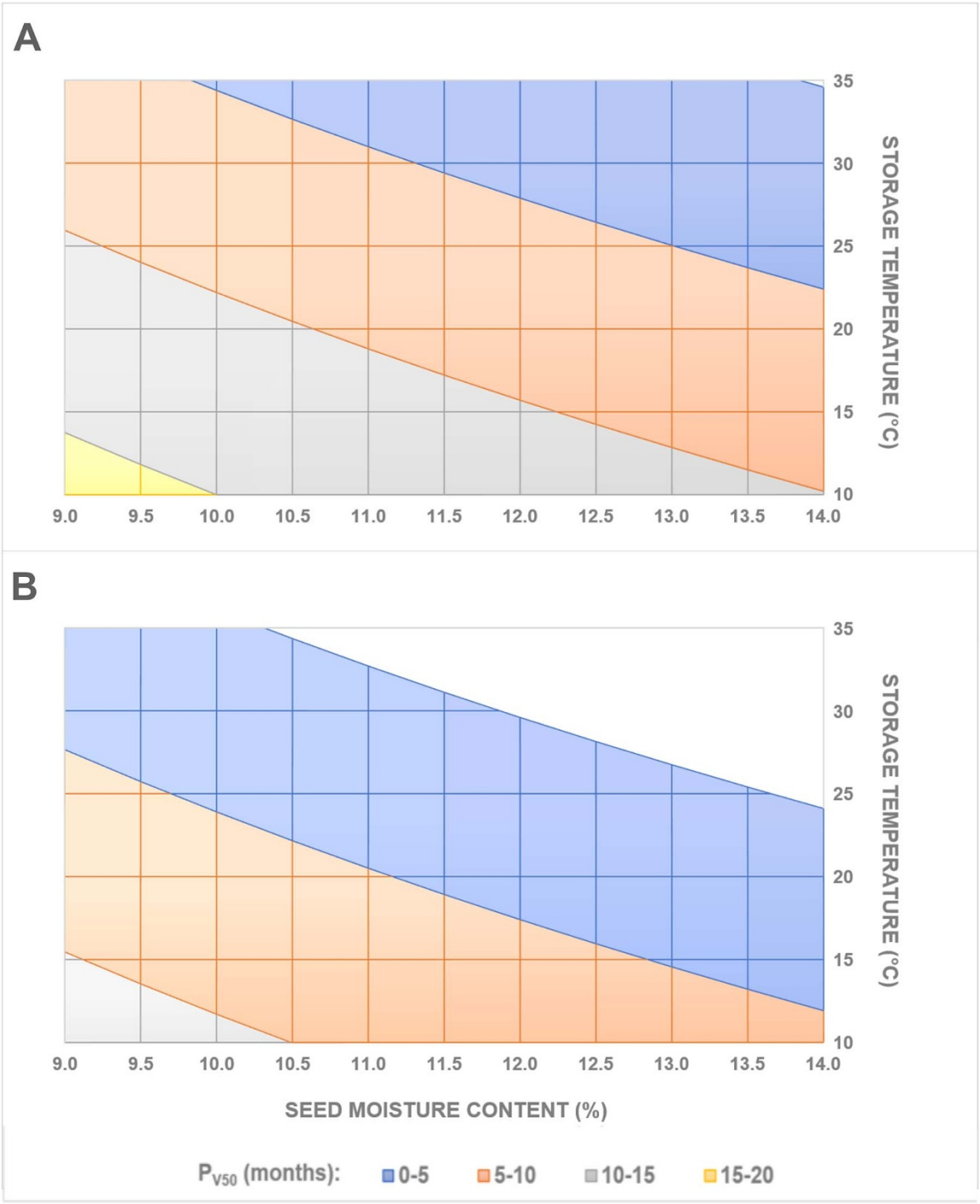


Figure 4. Simulation using Eq. 2 of seed moisture content (9–14%) and storage temperature (10–35°C) effects on P_{V50} under two damage scenarios: (A) low-damage levels (10% environmental damage, 0% seed coat cracking) and (B) high damage levels (30% environmental damage, 30% seed coat cracking). The white areas indicate P_{V50} values lower than 0.

relationship between these damages and vigour loss during storage. It is important to note that, although we measured several seed quality attributes to represent the main physiological differences among seed lots, other unmeasured seed lot characteristics may have also influenced the observed responses.

Based on the observed data, negative cumulative normal distribution equations (equation 1) and multiple linear regressions (equations 2 and 3) were fitted to quantify the relative effects of each factor on vigour decrease and to develop a predictive model of vigour dynamics under different storage conditions and damage levels (Table 2). The model (equations 1–3) provides a robust framework for describing vigour loss dynamics during storage in a real commercial seed production situation, capturing population variability within seed lots. The P_{V50} parameter, analogous to P_{50}, derived from the fitted curves and previously used in seed longevity models (Hay et al., 2018), proved effective also for quantifying

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vigour changes, allowing differentiation of seed lots with similar quality (Table 1). Similar population-based models have been used to predict seed viability but have not previously been applied to vigour parameters (Hay et al., 2022), although the model developed by Bradford et al. (1993) can be used to predict changes in germination rate during storage, which could potentially be used as a seed vigour index (Bradford and Bello, 2022). In population-based models, such as the one developed in this paper, changes in seed population behaviour can be accounted for by independent variation in the mean (i.e. P_{V50}), the standard (σ), or both (Bradford, 2002). The present model indicates that P_{V50} (i.e. the time required for initial vigour to decrease by 50%) and σ (i.e. the distribution of times for vigour to decline within the seed population) are independently affected by different factors (Table 2). While P_{V50} is affected by storage conditions (temperature and seed moisture content) and seed quality parameters (i.e. environmental damage and seed coat cracking), σ is only affected by storage conditions, particularly seed moisture content.

The model accurately described vigour behaviour for the original dataset (Figure 1) and predicted well for independent datasets from two cultivars and locations (Figure 2A, B). Egli et al. (1978) also reported no cultivar effect on changes in seed vigour during storage. This highlights the potential to apply the developed model to other genotypes and production regions. However, it was less precise for lots with high stink bug damage and seed coat cracking (Figure 2C), likely because it was calibrated using low-damage lots. This limitation highlights the need to account for seed damage levels when optimizing storage practices to preserve vigour (Figure 4). It is important to note that the model's lack of accuracy in predicting this specific situation does not undermine its potential use in real production systems. In most cases, harvested seed lots exhibit quality parameters similar to those of the lots used to develop the model (seed lots L1–L10), and it is uncommon to observe such high levels of bug damage and seed coat cracking as those recorded in the lot harvested in Salta (seed lots L22–L24). On the other hand, since the model was developed with data from seeds stored at only two temperatures (15 and 25 °C), extrapolation beyond this range requires caution. Testing vigour loss under a more comprehensive combination of temperatures and seed moisture contents is required to predict seed vigour loss across a broader range of storage conditions.

Vigour as a seed quality parameter is increasingly recognized in the seed industry and represents a key differentiator for companies. Although no official minimum vigour standards exist for commercialization, companies maintain internal thresholds. Modelling vigour – a more sensitive parameter than germination – allows early prediction of deterioration by the seed industry, providing valuable information for strategic management across production stages. The model presented in this work can infer storage potential via vigour P_{V50}, supporting internal quality control by adjusting monitoring intervals: shorter for lots with low P_{V50} or longer for those with high P_{V50}. Additionally, P_{V50} enables comparison of lots with similar quality and tailoring of storage conditions based on available options. Simulations further clarify how individual factors affect storability and vigour loss under specific conditions, facilitating interpretation and practical use of routine seed quality tests. Overall, this approach supports more informed decisions regarding conditioning, storage and marketing of seed lots, with the goal of preserving their vigour.

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References

Barrionuevo F, Panho MC, Meira D, Menegazzi CP, Marcante V, Linhares EN, Nascimento NG, Finatto T and Benin G (2025) Influence of seed physiological rupture on the physiological quality and storage of soybean seeds. *Seed Science and Technology* **53**(2), 147–158.

Bewley JD, Bradford KJ, Hilhorst HWM and Nonogaki H (2013) *Seeds. Physiology of Development, Germination and Dormancy*, 3rd Edn. New York: Springer Science and Business Media.

Bradford KJ (2002) Applications of hydrothermal time to quantifying and modelling seed germination and dormancy. *Weed Science* **50**(2), 248–260.

Bradford KJ and Bello P (2022) Applying population-based threshold models to quantify and improve seed quality attributes. In Buitink J and Leprince O (eds), *Advances in Seed Science and Technology for More Sustainable Crop Production*. Cambridge UK: Burleigh Dodds Science Publishing Limited, pp. 67–154.

Bradford KJ, Tarquis AM and Durán JM (1993) A population-based threshold model describing the relationship between germination rates and seed deterioration. *Journal of Experimental Botany* **44**(264), 1225–1234.

Carvalho ER, Mavaieie DPR, Oliveira JA, Carvalho MV and Rodrigues Vieira A (2014) Alterações isoenzimáticas em sementes de cultivares de soja em diferentes condições de armazenamento. *Pesquisa Agropecuária Brasileira* **49**(12), 967–976.

De Souza FH and Marcos-filho J (2001) The seed coat as a modulator of seed-environment relationships in fabaceae. *Revista Brasileira de Botânica* **24**(4), 365–375.

Di Rienzo JA, Casanoves F, Balzarini MG, González L, Tablada M and Robledo YC (2020) *InfoStat Versión 2020*. Argentina: Grupo InfoStat, Universidad Nacional de Córdoba.

Dickie JB, Ellis RH, Kraak HL, Ryder K and Tompsett PB (1990) Temperature and seed storage longevity. *Annals of Botany* **65**, 197–204.

Egli DB, White GM and TeKrony DM (1978) Relationship between seed vigor and the storability of soybean seed. *Journal of Seed Technology* **3**, 1–11.

Ellis RH (1988) The viability equation, seed viability nomographs and practical advice on seed storage. *Seed Science and Technology* **16**(1), 29–50.

Ellis RH (2022) Seed ageing, survival and the improved seed viability equation; forty years on. *Seed Science and Technology* **50**(1 Suppl), 1–20.

Ellis RH, Osei-bonsu K and Roberts EH (1982) The influence of genotype, temperature and moisture on seed longevity in chickpea, cowpea and soyabean. *Annals of Botany* **50**, 69–82.

Ellis RH and Roberts EH (1980) Improved equations for the prediction of seed longevity. *Annals of Botany* **45**(1), 13–30.

Ellis RH and Roberts EH (1981) The quantification of ageing and survival in orthodox seeds. *Seed Science and Technology* **9**(2), 373–409.

Ferreira FC, Villela FA, Meneghello GE and Soares VN (2017) Cooling of soybean seeds and physiological quality during storage. *Journal of Seed Science* **39**(4), 385–392.

Finch-savage WE and Bassel GW (2016) Seed vigour and crop establishment: Extending performance beyond adaptation. *Journal of Experimental Botany* **67**(3), 567–591.

Forti VA, Carvalho C, Ossamu Tanaka FA and Cicero SM (2013) Weathering damage in soybean seeds: Assessment, seed anatomy and seed physiological. *Seed Technology* **35**(2), 213–224.

França-neto JB and Krzyzanowski FC (2022) Use of the tetrazolium test for estimating the physiological quality of seeds. *Seed Science and Technology* **50**(1 Suppl), 31–44.

Hay FR, Davies RM, Dickie JB, Merritt DJ and Wolkis DM (2022) More on seed longevity phenotyping. *Seed Science Research* **32**, 144–149.

Hay FR, Valdez R, Lee JS and Santa Cruz PC (2018) Seed longevity phenotyping: Recommendations on research methodology. *Journal of Experimental Botany* **70**(2), 425–434.

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International Seed Testing Association (2018) *Handbook on Seedling Evaluation*, 5th Edn. Zürich, Switzerland: International Seed Testing Association.

ISTA (2022) *International Rules for Seed Testing 2022*. Zürich, Switzerland: International Seed Testing Association.

Marcos-filho J (2015a) *Fisiologia de Sementes de Plantas Cultivadas*, 2ndEdn. Londrina br:, ABRATES.

Marcos-filho J (2015b) Seed vigour testing: An overview of the past, present and future perspective. *Scientia Agricola* **72**(4), 363–374.

Moreano TB, Braccini AL, Scapim CA, Krzyzanowski FC, França-neto JB and Marques OJ (2011) Changes in the effects of weathering and mechanical damage on soybean seed during storage. *Seed Science and Technology* **39**, 604–611.

Parrish DJ and Leopold AC (1978) On the mechanism of aging in soybean seeds. *Plant Physiology* **61**(3), 365–368.

Powell AA (2022) Seed vigour in the 21st century. *Seed Science and Technology* **50**(1 Suppl), 45–73.

Smaniotto TAS, Resende O, Marçal KAF, Oliveira DEC and Simon GA (2013) Qualidade fisiológica das sementes de soja armazenadas em diferentes condições. *Revista Brasileira de Engenharia Agrícola E Ambiental* **18**(4), 446–453.

Teixeira SB, Zorato MF and Meneghello GE (2024) Implications of seed coat cracking on soybean seed quality. *Journal of Seed Science* **46**(3). https://doi.org/10.1590/2317-1545v46288842

TeKrony DM and Egli DB (1977) Relationship between laboratory indices of soybean seed vigor and field emergence. *Crop Science* **17**, 573–577.

TeKrony DM, Egli DB and Phillips AD (1980) Effect of field weathering on the viability and vigor of soybean seed. *Agronomy Journal* **72**, 749–753.

Torres Licursi Vieira BG, Barbosa GF, Barbosa RM and Vieira RD (2013) Structural changes in soybean seed coat due to harvest time and storage. *Journal of Food Agriculture and Environment* **11**(1), 625–628.

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