

# Predicting soybean seed longevity under ambient storage through multivariate viability and vigor analysis

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**Abstract.** *Zalama MT, Leilah AAA. 2025. Predicting soybean seed longevity under ambient storage through multivariate viability and vigor analysis. Asian J Agric 9: 702-711.* The current study examined the longevity of the soybean seed cultivar (Giza 111) under ambient storage conditions in Dakahlia, Egypt, from July 2023 to June 2024. Three lots of seed from different sources were observed for up to 360 days to predict seed longevity and to determine storage parameters for warehouse management. Initial seed quality was estimated, then a simplified viability equation,  $v = Ki - (1/\sigma) P$ , was applied to predict seed longevity during the storage period. Significant differences were noticed among seed lots. Seed lot 01 (Legumes Department, FCRI, ARC) exhibited the best seed viability, with the highest storage index ( $\sigma = 120$  days), longest half-viability period ( $P50 = 151$  days), and slowest deterioration rate ( $tg\beta = -0.0008$ ), indicating superior vigor during storage. In contrast, seed lots 02 and 03, obtained from the private sector, showed reduced viability, with Lot 03 exhibiting the lowest ( $\sigma = 90$  days,  $tg\beta = -0.011$ ,  $P50 = 79$  days). Linear regression showed seed viability decline rates differed: Lot 01 (slowest, -2.50), Lot 02 (moderate, -2.73), and Lot 03 (fastest, -3.34), confirming relative deterioration speeds. Pearson correlation analysis showed a strong positive correlation between probit viability and seed vigor indices, including germination ( $r = 0.946$ ), accelerated aging ( $r = 0.945$ ), seedling dry weight ( $r = 0.925$ ), and vigor index II ( $r = 0.935$ ). Quantitative data further supported the correlation between probit viability and vigor parameters. This study demonstrated that a simplified viability equation effectively predicted the longevity and vigor of soybean seeds from different sources stored under ambient conditions in Dakahlia, Egypt. Significant differences in viability and deterioration rates among seed lots underscore the equation's value for practical seed storage monitoring, improved ambient storage management, and enhanced seed inventory control and quality preservation through accurate performance prediction.

**Keywords:** Ambient storage, probit viability, seed deterioration, seed lots, seed vigor

## INTRODUCTION

Seed longevity research has progressed from observation to predictive modeling (Ellis 2022; Hay et al. 2022). Ewart's 1908 seed classification by lifespan-initiated seed storage science, noting species variation and environmental influence (Roberts 1973; FAO 1999). Harrington's rules quantified this, showing that a 5.6°C temperature increase or 1% moisture increase halves seed lifespan (Harrington 1972). Mathematical modeling began in the 1970s with Roberts' (1973) equations predicting seed longevity. These models suggested seed survival curves follow cumulative normal distributions, enabling statistical prediction. Roberts' work established that seed death distributions follow negative cumulative normal curves, time ranges are proportional to average viability, and environmental factors linearly affect longevity (Roberts 1973; Zhou et al. 2016). This equation enabled predictions across conditions and aided seed banking (Ellis and Roberts 1980; Ellis 2022).

Building upon Roberts' framework, simplified models were developed to address the complexity and data needs of comprehensive viability equations, enabling practical application for ambient storage (Andreoli 1997). These models retain mathematical rigor while decreasing data

needs and improving accessibility. Seed longevity estimates are crucial. Roberts (1973) and Ellis and Roberts (1980) created equations for predicting cereal grain longevity:  $v = ki - (1/\sigma) p$ , where  $v$  is probit viability,  $Ki$  is initial probit viability, and  $\sigma$  is the standard deviation. The slope ( $1/\sigma$ ), denoted as  $tg\beta$ , reflects the seed deterioration rate and half viability period ( $P50$ ). This equation is useful for predicting soybean seed storage (Tekrony et al. 1993; Basso et al. 2018; Batista et al. 2021; Muhamad et al. 2024). Accelerated aging tests evaluate seed vigor and predict storage behavior (ISTA 2024), simulating extended storage. Initially, they predicted relative storability, correlating with warehouse deterioration (Zalama 2021; Silva et al. 2024). Correlating accelerated aging with ambient storage is challenging (Tekrony 1995). Vigor testing and proper storage are essential for preserving seed quality (Zalama et al. 2024).

Soybean seed quality is vulnerable to damage both before and after harvest. Due to their delicate seed coat and embryo orientation, soybeans are susceptible to internal fractures from impacts during handling, particularly when dry. This mechanical damage reduces seed viability during storage, which is also affected by initial seed quality and storage conditions. Soybeans, especially in tropical and subtropical climates, are difficult to store due to their rapid

deterioration. High oil content accelerates lipid oxidation and membrane degradation, leading to the quick deterioration of these short-lived seeds (Muhamad et al. 2024). Viability can decline significantly within a single season (Tekrony et al. 1993), posing challenges for seed producers, farmers, and conservation, especially when controlled storage is limited (Coradi et al. 2020). High temperature and humidity exacerbate deterioration through biochemical processes, membrane damage, and increased microbial/insect activity (Bernal-Lugo and Leopold 1998; Ranganathan and Groot 2023). While ideal storage requires temperatures below 10°C and humidity below 50% (Ellis 2022), these conditions are often impractical, emphasizing the importance of predictive models for assessing seed viability under variable ambient conditions (Tekrony et al. 1993; Muhamad et al. 2024). For example, Mahlangu et al. (2024) demonstrated that a viability equation accurately predicts soybean seed deterioration during ambient storage, with moisture and environmental fluctuations accelerating viability loss.

A simplified viability equation is crucial for estimating soybean seed viability and vigor during storage. It allows for practical and accurate prediction of seed longevity under variable ambient conditions, aiding seed producers and warehouse managers in optimizing storage and inventory turnover. This prevents losses from seed deterioration and ensures high germination and vigor at planting, directly impacting crop yield and quality, particularly in developing regions where ambient storage is prevalent. The simplified equation provides an effective predictive tool without complex procedures. Key references supporting these points include Ellis and Roberts (1980), who established foundational seed viability models that have been adapted in simplified forms to suit uncontrolled ambient conditions; Andreoli (1997) demonstrated the utility of a simplified viability equation for maize and soybean seeds under variable conditions; and more recent studies that highlight the importance of maintaining seed vigor for storage management and successful field performance (Coradi et al. 2020; De Vitis et al. 2020; Ellis 2022; Hay et al. 2022; Muhamad et al. 2024). These studies collectively show the practical benefits of simplified viability models for managing seed storability under realistic storage environments.

This research evaluates the efficiency of a simplified viability equation in predicting soybean seed lot longevity by assessing key parameters including initial seed quality, storage index ( $\sigma$ ), deterioration rate ( $tg\beta$ ), and time to reach 50% viability (P50) under ambient storage conditions, comparing longevity performance across different seed lots, and examining relationships between laboratory vigor tests, longevity predictions, and seedling emergence outcomes.

## MATERIALS AND METHODS

### Seed materials

Soybean (*Glycine max* L.) cultivar (Giza 111) seeds were obtained from three lots: one from the Legumes

Department, FCRI, ARC, and two from the Seed Central Administration for Seed Testing and Certification procured from the private sector (Table 1). The investigation was conducted in the Preservation Laboratory, Seed Technology Research Unit, Mansoura City, STRD, FCRI, ARC, Egypt.

### Storage experiment setup

Seed lots were conditioned, and their initial quality and viability were assessed according to ISTA (2024) guidelines. Unrefined seeds were discarded, and a representative sample of the remaining high-quality soybean seeds was collected from each lot before storage (time = 0) to determine initial seed status. Initial seed moisture content (fresh weight basis) was determined using the oven-drying method (20 g seed at 103°C for 17 hours). An Accelerated Aging Test (AAT) was conducted using four replicates of 100 seeds per treatment, which were placed in AA containers at 41°C and 100% relative humidity for 72 hours. Standard germination tests were performed on both normal and aged seeds, and germination rates were calculated as the percentage of germinated seeds relative to the total number of seeds evaluated (Table 1).

### Experimental design and sample size

Three soybean seed lots (Lot 01, Lot 02, and Lot 03) were evaluated for viability after 30, 60, 90, 120, 150, 180, 240, and 360 days of storage using a Completely Randomized Design (CRD) with four replicates per treatment. Each storage duration was treated as a separate experiment, with four replicates of 100 seeds (approximately 60 g) from each lot tested, totaling 400 seeds per lot and roughly 1.5 kg for the entire experiment. Seeds were bagged in multiwall paper bags and stored under ambient conditions (annual average 22.4°C and 75% RH) in the Preservation Laboratory. Samples were taken after every storage period to estimate viability measurements.

### Viability measurements

**Probit viability (v)** converts germination data to Probit percentage viability against storage time, generating a linear relationship with a negative slope ( $1/\sigma$ ) as described by Finney (1971).

**Table 1.** Initial seed status obtained by soybean seed lots, Cultivar Giza 111

Seed lots source	Moisture content FW basis (%)	Initial germination (%)	Accelerated aging test (%)
Lot 01 (Legumes department)	11.85	94.25	91.02
Lot 02 (private sector 01)	12.08	92.65	89.68
Lot 03 (Private sector 02)	12.24	87.35	84.14

**Storage index ( $\sigma$ )** for soybean seed stored in ambient storage conditions for all three seed lots, as a function of the time taken in days, for the germination to fall to a certain germination value in the accelerated aging test. The basal hypothesis suggests that the accelerated aging conditions symbolize the deterioration rates of the seed are similar to those under ordinary storage conditions (Ellis and Roberts 1980).

**Simplified viability equation** recognizes that seed survival curves represent cumulative normal distributions with a negative slope ( $1/\sigma$ ). It was performed when seed germination data points are plotted as a probit percentage against time, and then straight lines of negative slope are produced. Therefore, remaining viability (seed survival or seed deterioration rate) can be predicted by the probit viability equation model (Ellis and Roberts 1980). Where ( $v$ ) is the percentage of probit viability at storage time ( $p$ ), with ( $K_i$ ) as the initial probit viability, and ( $\sigma$ ) represents the standard deviation of the distribution of deaths over time.

$$v = k_i - \left(\frac{1}{\sigma}\right) \cdot P$$

**Seed deterioration rate (tg $\beta$ )** expressed as the angular coefficient of the Probit viability plot versus storage time, which directly measures the survival curve slope ( $1/\sigma$ ), as described by Finney (1971).

**The half-viability period (P50)** is the time at which a seed lot is projected to lose half its germinability under specific storage conditions. It is determined by using the following equation, by setting the Probit value ( $y = 5.00$ );

$$x = \frac{\text{Probit value } (y) - \text{Intercept}}{\text{Slope}}$$

**Regression equation** based on the method of Finney's (1952) and later editions induced by Agresti (2012), is proposed to model the relationship between log storage period (time to lose one probit of viability) as the independent predictor and probit values as the dependent response, where  $a$  is the intercept representing the expected seed viability ( $y$ ) when the log of the storage period ( $x$ ) is zero,  $b$  is the slope, and ' $e$ ' is the error term, as follows:

$$y = a + bx + e$$

#### Seed vigor experiment setup

For the seed vigor experiment, three storage durations (180, 270, and 360 days) were selected to evaluate the seed vigor of the same three soybean seed lots (Lot 01, Lot 02, and Lot 03). A Completely Randomized Design (CRD) with four replicates per treatment was used. Each replicate consisted of 100 seeds (approximately 15 g), resulting in 400 seeds per seed lot per storage duration. Samples were taken after each storage period to evaluate the changes in seed vigor over time, following ISTA (2024) guidelines, as follows;

Soybean seeds were surface-sterilized with 0.1% sodium hypochlorite, rinsed twice, and dried. Germination was tested under ideal laboratory conditions. For each

treatment, 20 seeds were germinated in 15 cm Petri dishes on moistened Whatman No. 1 filter paper; four dishes constituted one replicate. Dishes were incubated in a growth chamber at 25°C and 80% relative humidity, with filter papers occasionally moistened with 10 ml of distilled water. Seed vigor was monitored daily for 8 days based on germination.

#### Physiological seed vigor tests

**Germination percentage (G%)** was determined by counting viable seedlings 8 days after sowing;  $G\% = (\text{Number of germinated seeds} / \text{Total seeds evaluated}) \times 100$ .

**Mean germination time (MGT, day)** was determined as  $MGT = \Sigma (n \times D) / \Sigma n$ , where  $n$  is the number of seeds germinated on day  $D$ , and  $D$  is the number of days since the beginning of the test.

**Seedling dry weight (mg seedling<sup>-1</sup>)** was determined by randomly selecting and weighing 30 seedlings (10 per replicate) seven days post-sowing.

**Seedling vigor index (SVI-II)** was calculated according to the formula:  $SVI-II = \text{Seedling dry weight (mg)} \times \text{Germination percentage}$ .

**Electrical conductivity test ( $\mu\text{S cm}^{-1} \text{g}^{-1}$ )** was tested on four sterilized seed samples per treatment (0.1% NaOCl, 10 min rinse) incubated in 100 mL water (25°C, 24 h). Leachate conductivity was measured and corrected to calculate electrolyte leakage, as follows:  $\text{Electrolyte leakage} = (\text{leachate conductivity} - \text{distilled water conductivity}) / \text{seed sample weight (g)}$ , expressed in  $\mu\text{S cm}^{-1} \text{g}^{-1}$ .

#### Statistical analysis

For the seed storage experiment, data were analyzed using Analysis of Variance (ANOVA) according to the Completely Randomized Design (CRD) with four replicates per treatment. Each storage duration was treated as a separate experiment as well as a fixed factor, and seed lots were considered to assess their effects on seed viability parameters. While Probit viability was measured using the guidelines of the simplified viability equation of Ellis and Roberts (1980).

Regression analysis: The relationship between seed viability and storage duration was modeled using a linear regression approach based on the method of Finney (1952) and extended by Agresti (2012). The probit value of seed viability was set as the dependent variable, and the logarithm of the storage period was the independent predictor. The regression equation is expressed as:

$$y = a + bx + e$$

Where, ( $a$ , intercept) represents the expected viability when the log storage period ( $x$ ) is zero, ( $b$ , slope) indicates the rate of viability decline, and ( $e$ ) is the error term accounting for residual variance.

For the vigor experiment, ANOVA was also applied using a CRD with four replicates per treatment to compare seed vigor across three selected storage durations (180, 270, and 360 days) and three seed lots. Vigor was assessed

using standardized tests (ISTA 2024). Correlation analyses using Pearson's coefficients quantified relationships among vigor metrics and viability results.

Factorial combined analysis was used for data storage and vigor experiments, with duration treated as continuous and seed lot effects included. ANOVA within a CRD framework was used to assess treatment effects (Gomez and Gomez 1984). Tukey HSD at the 0.05 level of probability was used to determine significant mean differences. IBM SPSS Statistics (Ver. 25) and Microsoft Excel (2023) were used for data analysis and graphing.

## RESULTS AND DISCUSSION

Soybean seed lots exhibited varying longevity and viability after 360 days of ambient storage (Table 2). Lot 01 demonstrated the highest initial viability (probit 6.57), storage index (120 days), and the slowest deterioration rate (-0.0008), resulting in the highest mean viability (probit 5.15). Lot 02 showed slightly reduced initial viability (2%), a lower storage index (8.3%), and a substantially increased deterioration rate compared to Lot 01, leading to a 5% decline in mean viability. Lot 03 experienced even greater declines, with a lower initial viability (6.5%), a markedly reduced storage index (25%), and the highest deterioration rate increase, resulting in a 17.5% reduction in mean viability. These results indicate Lot 01 (Legumes Department, FCRI) maintained superior seed quality during storage, while Lots 02 and 03 (Private sectors), especially Lot 03, were more prone to rapid viability loss, highlighting the impact of seed source and handling on storage performance. The simplified viability equation effectively monitored seed health during storage.

Among all other storage techniques in legumes, this viability equation approach presents practicality and efficacy. Though the Ellis-Roberts equation to predict viability in seeds through probit analysis also recognizes differential rates of deterioration depending on the lot and genotype in seeds (Surki et al. 2012; Righetti et al. 2015), environmental storage conditions, i.e., temperature and relative humidity (Zalama et al. 2024), seed backing materials (Baributsa and Baoua 2022), and initial seed quality (Mahlangu et al. 2024). The agreement between this model and physiological tests was found, such as lowering seed moisture content to 12-14%, which reduces deterioration. Mahlangu et al. (2024) noted that storage under the recommended moisture content preserves viability and increases storage life. Monitoring lipoxygenase and antioxidative enzyme activity, indicators of enhanced longevity through lipid peroxidation suppression (Rao et al. 2023). Soybean seed quality relies on cold, stable storage. Controlled conditions preserve germination. High temperature and fluctuating humidity accelerate deterioration; stable storage extends seed life (Koskosidis et al. 2022). As highlighted by Zalama et al. (2024). They indicated that cold storage (5°C and 30% RH) significantly enhances the storability and quality of soybean seeds compared to open storage, exhibiting minimal deterioration over time, whereas open storage

experienced rapid declines due to increased metabolic activity and susceptibility to fungal infections. Baributsa and Baoua (2022) found that hermetic bags are crucial for maintaining soybean seed quality in environments with high relative humidity. They prevent moisture intrusion, which can cause seed deterioration. Zalama (2021) similarly found that cold storage (5°C) in airtight polyethylene bags with low moisture content (30±2% RH) effectively maintained seed viability and vigor, highlighting the importance of proper environmental conditions and low moisture levels. It is consistent with the behavior of soybean Lot 01, where a combination of better initial seed quality and storage tolerance may have been the reason for the higher storage indices and slower deterioration rates under natural conditions. Genotypic as well as environmental factors affect the seed maturation stage and give additional value to the integration of predictive formulas with a wide characterization of seed quality in order to facilitate informed storage decisions (Batista et al. 2021). Collectively, the ability to maintain seed viability depends not only on initial seed quality but also on efficient storage conditions. The viability equation in this approach quantifies the longevity regardless of seed storage systems.

The linear regression analysis using the viability equation reveals clear percentage differences in seed longevity among the three soybean lots, highlighting variability in their initial viability and deterioration rates (Table 3). Overall, Lot 02 exhibited about a 9.2% steeper deterioration rate than Lot 01, causing a roughly 20.5% reduction in the half-viability period, while Lot 03 showed an even faster deterioration at 33.6% steeper than Lot 01, resulting in a nearly 48% shorter half-viability. These substantial differences reflect how variations in storage performance can critically affect seed longevity.

Using the linear regression equation at specific storage durations (i.e., 6, 12, 18, and 24 months), predicted seed viability values further emphasize these differences. At 6 months, Lot 02 and Lot 03 still show slightly higher viability levels (by approximately 9.6% and 13.5%, respectively) compared to Lot 01, indicating better initial vigor. However, this trend reverses over longer storage times; at 12 months, Lot 02's viability drops 9% below Lot 01, and Lot 03's declines significantly more, nearly 34% lower. By 18 months, Lot 02's viability aligns closely with Lot 01, showing only about a 1% higher value, whereas Lot 03 continues to deteriorate rapidly, with viability approximately 36% lower than Lot 01. Extending to 24 months, the gap widens with Lot 2's viability 13% lower and Lot 3's nearly halved (45% lower) compared to Lot 1. This pattern confirms that although some lots may start with higher initial viability, their faster deterioration rates lead to reduced long-term seed performance, underscoring the importance of accounting for both initial quality and decline rates in seed storage management decisions.

These variant results appear in line with the current theories of seed aging; slower rates of deterioration seem to be related to enhanced tolerance to oxidative stress and the capacity for cellular repairs (Lehner et al. 2008). Although Nagel and Börner (2010) proposed that the P50 changes

would be linked to oxidative damage and electrolyte leakage and, thus, might indicate the ability of a seed lot to retain viability during storage (Batista et al. 2021). Finally, these findings highlight the importance of initial seed quality in seed storage longevity, which will have practical implications on the marketing of seed lots prepared for planting, how preservation practices are conceived, and how seed banks are managed (Righetti et al. 2015; Lima et al. 2017; Basso et al. 2018; Zalama 2021).

Line fit plots describe the relationship between probit viability and log storage period for three soybean seed lots under ambient storage conditions (Figure 1). Each plot displays the regression equation and P50 point (time to lose 50% of viability). Lot 01 exhibited the slowest viability loss values, with a slope of -2.5075 and an intercept of 10.484, with the highest P50 of 2.18 (~151 days), indicating the longest storage longevity. Lot 02 deteriorated slightly faster; slope = -2.7255, intercept = 10.71, with a P50 of 2.08 (~120 days). While Lot 03 showed the most rapid viability loss, slope = -3.3433, intercept = 11.359, with the lowest P50 of 1.90 (~79 days).

The plots visually confirm the regression statistics, with dotted lines indicating the P50 crossing. These graphs illustrate the influence of initial seed lot quality on deterioration patterns, where higher initial quality (Lot 01) correlates with slower viability decline. This visual representation provides insight into predicting seed viability during storage, assisting in storage management decisions. Probit analysis of full germination survival curves converts germination data to probit percentage viability versus storage time. Then, the resulting half-viability (P50) effectively assesses seed longevity and predicts storage behavior under ambient conditions (Ellis and Roberts 1980). The obtained results demonstrate that P50 is a helpful indicator for estimating soybean seed

storage capacity due to its strong correlation with longevity and vigor, which can be integrated into traditional seed analyses.

Additionally, the seed maturation is also likely to have played a role in seed durability. Lot 01's durability likely benefited from optimal seed maturation. The comparatively faster decline in fresh weight observed in Lots 02 and 03 may stem from differences in initial seed quality and storage stability, emphasizing the importance of these factors for long-term seed storage. Regression-based predictions offer a practical tool for seed storage managers, enabling differentiation between seed lots and forecasting viability loss. This approach can improve internal quality control in seed analysis laboratories and inform decision-making in seed companies (Nagel and Börner 2010; Batista et al. 2021), as well as optimize seed lot management and minimize storage losses (Surki et al. 2012; Righetti et al. 2015).

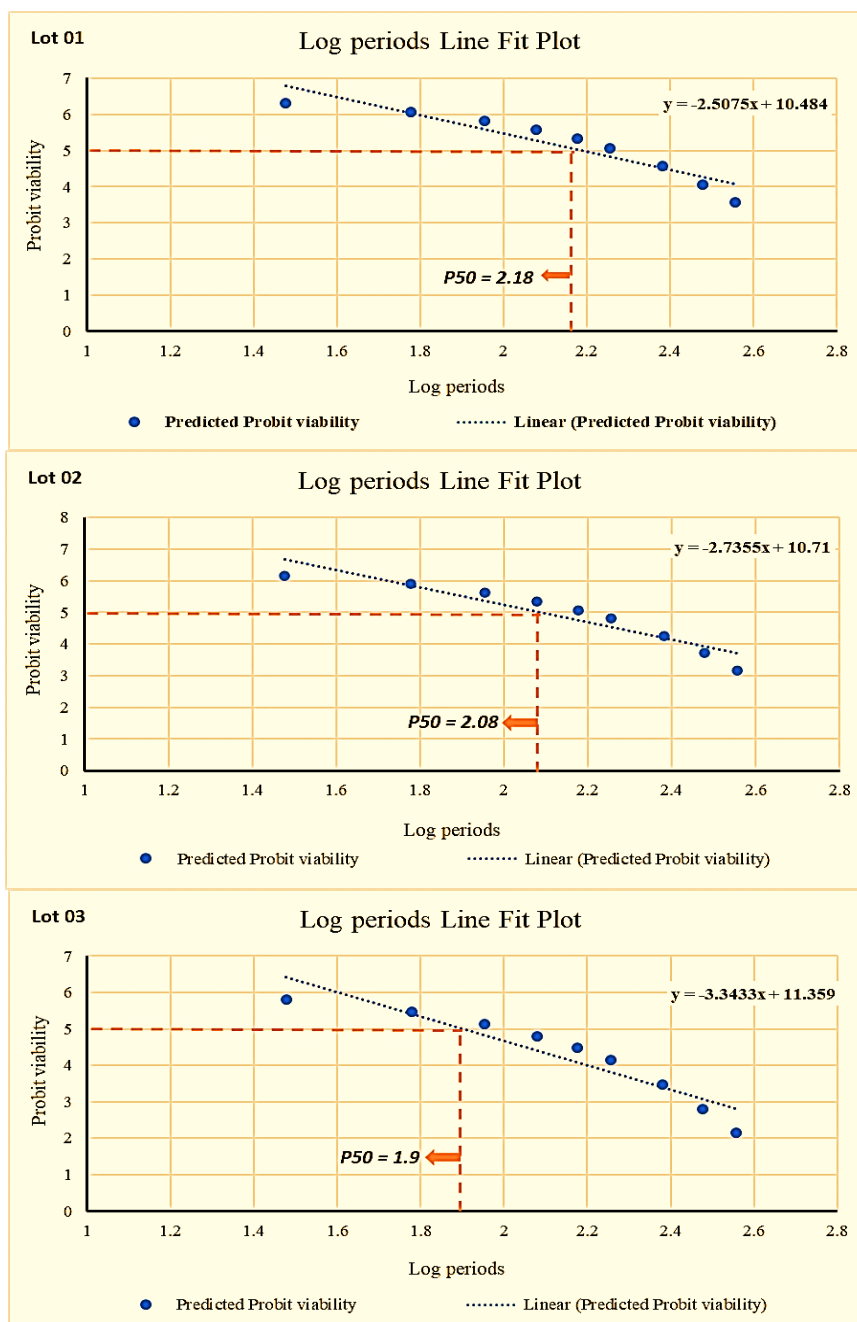
Table 4 shows significant differences ( $P < 0.05$ ) in germination and vigor among the three seed lots. Lot 01 (Legumes Department) exhibited superior seed quality, with the highest germination (79.1%) and accelerated aging test (AAT) performance (70.3%). Lot 01 outperformed Lot 02 (Private Sector 1) by 7.9% in germination and 13.6% in AAT, and Lot 03 (Private Sector 2) by 22.3% and 30.9%, respectively. Lot 03 showed the poorest performance, while Lot 02 was intermediate. Electrical conductivity values also reflected quality differences: Lot 01 had the lowest conductivity ( $56.8 \mu\text{S cm}^{-1} \text{g}^{-1}$ ), while Lots 02 and 03 showed increases of 14.6% and 37.9%, respectively, indicating greater cellular damage. These findings suggest that seed lot selection, influenced by factors such as production practices, storage, or genetics, significantly impacts soybean seed performance and should be carefully evaluated in quality assessment.

**Table 2.** Probit viability ( $v$ ) parameters estimated using the simplified longevity equation [ $v = Ki - (1/\sigma) P$ ] for three soybean seed lots stored under ambient conditions for 360 days

Seed lots	Initial probit viability (Ki)	Storage index ( $\sigma$ , days)	Deterioration rate $\text{tg}\beta$ ( $-1/\sigma$ )	Probit $v$ at storage time			Mean probit ( $v$ ) over storage period (360 days)
				180 days	270 days	360 days	
Lot 01	6.57	120	-0.0008	5.07	4.32	3.57	5.15 (~356 days)
Lot 02	6.44	110	-0.009	4.80	3.98	3.17	4.89 (~282 days)
Lot 03	6.14	90	-0.011	4.14	3.14	2.15	4.25 (~176 days)

**Table 3.** Probit viability induced by linear regression statistics using the equation:  $y = a + bx + e$  ( $y$ ) predicted seed viability, ( $a$ , intercept) the initial probit viability, ( $b$ , slope) probit viability by the log of storage period, ( $x$ ) log of the storage period, ( $e$ ) error term, including P50 (Half viability period)

Seed lots	Regression coefficient					Half viability (P50, days)
	Probit Intercept (a)	Probit/log day (Slope, b)	SE (Slope)	Lower 95%	Upper 95%	
Lot 01	10.48	-2.50	0.34	-3.32	-1.69	2.18 (~151 days)
Lot 02	10.71	-2.73	0.37	-3.62	-1.84	2.08 (~120 days)
Lot 03	11.35	-3.34	0.45	-4.42	-2.25	1.90 (~79 days)



**Figure 1.** Probit viability versus log storage period for three soybean seed lots under ambient storage conditions (variable Temp and RH), with visual estimation of half-viability period (P50). Lot 01 obtained from the Legumes Department, FCRI, Lot 02 and 03 obtained from the Private sector. P50 is the median effective log period for 50% probit viability. P50 is determined by identifying the time (in log of time storage) corresponding to a Probit viability of 50% (y axis of Probit = 5) and then taking the antilog of time storage (x axis). In the linear regression equation  $y = b(x) + a$ , probit viability (y) is predicted based on the log period (x). A negative slope (b) indicates decreasing viability with increasing log period, and the intercept (a) represents the predicted probit viability when  $x = 0$

Table 5 shows that seed vigor under ambient storage varied significantly depending on the interaction between seed lot and storage period. Lot 01 maintained the highest vigor, with germination decreasing by 12.3% and Accelerated Aging Test (AAT) results decreasing by 15.8% between 180 and 360 days. Lot 02 showed intermediate performance, with germination decreasing by 12.4% and AAT results decreasing by 20.2% over the same period. While the seed lot 03 exhibited the most deterioration, with

germination decreasing by 20.9% and AAT results decreasing by 25.5%. Electrical conductivity increased for all lots, indicating membrane deterioration, with increases of 83.3% in Lot 01, 37.8% in Lot 02, and 28.0% in Lot 03. These findings suggest that initial seed lot quality strongly affects storage longevity, with higher quality lots maintaining better viability and vigor under ambient conditions.

Seed vigor is widely related to seed viability and longevity, as confirmed in this study, where superior

soybean seeds (Lot 01) gained both the highest predicted viability and vigor indices. High-vigor seeds typically germinate faster and more uniformly, resulting in more reliable and stable seedlings before and after storage. On the contrary, low-vigor seeds germinate later and less uniformly, displaying increased sensitivity to environmental stresses, delayed emergence, and shorter storage times than predicted by viability models. These findings align with research on invasive plants (Prado et al. 2019; Fenollosa et al. 2020), soybeans (Batista et al. 2021; Zalama et al. 2024), and onion seeds (Zalama 2021), all highlighting vigor as a critical seed quality attribute strongly linked to physiological performance and storability. While viability tests are important, vigor assessment is also required for comprehensive seed quality evaluation because vigor is vast, and viability tests alone are insufficient to predict field performance. Seed vigor tests, like accelerated aging, cold, and electrical conductivity, are sensitive measures for detecting early deterioration in seeds, aiding seed lot management (Matera et al. 2019; Prado et al. 2019; Silva et al. 2024). Although high-vigor seeds result in faster, more uniform emergence, greater stress tolerance, and improved stand and yield,

positively impacting plant productivity (Bagateli et al. 2019).

Through the process of deterioration, seed reserves of carbohydrates, proteins, and lipids, which are the essentials for germination and early seedling growth, are weakened. This deterioration becomes clear through high rates of accelerated senescence and electrolyte leakage, both sensitive indicators of seed deterioration. Seed lot salt leakage variations may stem from seed coat permeability differences, affecting moisture absorption and deterioration rates. Chandra et al. (2020) found that lower permeability delays water ingress, protecting seed integrity, while high permeability accelerates water uptake and deterioration. Abati et al. (2022) linked higher seed coat lignin to lower water absorption and better storage, highlighting seed coat composition. Although Vijayan et al. (2023) found that differences in biochemical composition between black and white soybean seed coats significantly affect water permeability, influencing seed coat impermeability and seed longevity. Consequently, deterioration and decline in the content of seed reserves cause shorter storage lives, poor seed quality, decline in germination and seedling vigor, and plant establishment.

**Table 4.** The mean values for germination percentage (G%), Accelerated Aging Test (AAT%), electrical conductivity (EC,  $\mu S\ cm^{-1}\ g^{-1}$  dry seed), mean germination time (days), seedling dry weight (mg), and seedling vigor index (II), influenced by three lots of soybean seeds subjected to ambient storage conditions over three different storage periods

Factors treat/Traits	G%	AAT%	EC ( $\mu S\ cm^{-1}\ g^{-1}$ )	MGT (day)	SDW (mg)	SVI-II
Seed Lots (A)						
Lot 01 (Legumes Department)	79.1a	70.3a	56.8c	3.7a	0.28a	22.5a
Lot 02 (Private Sector 1)	73.3b	61.9b	65.1b	3.6a	0.24b	18.4b
Lot 03 (Private Sector 2)	64.7c	53.7c	78.8a	4.1a	0.20c	13.6c
Storage Periods (B)						
180 days	78.5a	69.4a	57.1c	3.4b	0.27a	22.0a
270 days	72.0b	61.2b	67.5b	3.9ab	0.24b	17.9b
360 days	66.7c	55.4c	76.1a	4.1a	0.21c	14.6c
Grand Means	72.4	62.0	67.0	4.0	0.2	18.2
CV	1.4	1.20	3.3	13.4	3.1	3.3

Note: Within each column, mean values followed by different letters indicate significant differences among treatments (Tukey's HSD,  $P < 0.05$ ). Values sharing a letter are not significantly different

**Table 5.** All-Pairwise comparisons test of seed vigor parameters as affected by the interaction between three lots of soybean seeds over three different storage periods, subjected to ambient storage conditions. G% (Germination percentage), AAT% (Accelerating aging test), EC (Electrical conductivity test), MGT (Mean germination time), SDW (Seedling Dry Weight), and SVI-II (Seedling Vigor Index based on dry weight)

Interaction treat/Traits	G%	AAT%	EC ( $\mu S\ cm^{-1}\ g^{-1}$ )	MGT (day)	SDW (mg)	SVI-II
Lot 01 × 180 days	84.8a	76.5a	48.7e	3.54ab	0.31a	26.5a
Lot 01 × 270 days	78.1b	70.3b	57.4d	3.74ab	0.28b	22.1b
Lot 01 × 360 days	74.4c	64.3c	64.4c	3.84ab	0.25c	18.7c
Lot 02 × 180 days	78.2b	69.3b	53.6de	2.93b	0.28b	22.2b
Lot 02 × 270 days	73.3c	61.1d	66.3c	3.86ab	0.25c	18.2cd
Lot 02 × 360 days	68.5d	55.3e	75.2b	4.08ab	0.21de	14.8e
Lot 03 × 180 days	72.4c	62.3d	69.1c	3.86ab	0.23cd	17.1d
Lot 03 × 270 days	64.5e	52.3f	78.8b	4.05ab	0.21e	13.3f
Lot 03 × 360 days	57.3f	46.4g	88.5a	4.34a	0.18f	10.5g
Tukey HSD (0.05)	2.39	1.79	5.24	1.2	0.018	1.4

Note: Within each column, mean values followed by different letters indicate significant differences among treatments (Tukey's HSD,  $P < 0.05$ ). Values sharing a letter are not significantly different

**Table 6.** Correlation coefficients and covariance analysis between probit viability and seed vigor parameters for evaluating soybean seed lot quality

Pearson's correlation	r	P-value	Variance	Variance-Covariance matrix		
Probit × G%	0.946	0.004	Probit	0.78	Probit × G%	6.56
Probit × AAT%	0.945	< 0.001	G%	61.37	Probit × AAT%	7.60
Probit × EC	-0.949	< 0.001	AAT%	82.63	Probit × EC	-10.3
Probit × MGT (day)	-0.541	0.02	EC	150.6	Probit × MGT (day)	-0.28
Probit × SDW (mg)	0.925	0.01	MGT (day)	0.34	Probit × SDW (mg)	0.03
Probit × SVI-II	0.935	0.01	SDW (mg)	0.001	Probit × SVI-II	3.98
			SVI-II	23.14		

Table 6 emphasizes the correlation and covariance analyses, demonstrating a clear and statistically significant relationship between probit viability and seed vigor parameters tested on soybeans, thus enhancing the strong relationship between seed vigor and longevity prediction. All selected parameters represent the seeds' ability to germinate faster, emerge uniformly, and stand up to aging stresses, which is important for the successful establishment of a soybean seedling. Among these, strong positive correlations of probit viability with germination percentage (0.946), accelerated aging test (0.945), seedling dry weight (0.925), and seedling vigor index II (0.935) indicate that seeds predicted to maintain higher viability are also expected to express more advanced physiological performance and sturdiness during vigor assessments.

On the other side, probit viability was also shown to have strong negative correlations with electrical conductivity (-0.949) and with the mean germination time (-0.541), which provides further insight into how membrane integrity and germination speed correlate negatively with seed deterioration. Whereas electrical conductivity is a sensitive measure of leakage across the membranes, higher electrical conductivity readings correlate with high seed deterioration and aging. In addition, a faster germination time correlating with higher viability is likely to suggest that seeds that remain vigorous tend to germinate earlier and more uniformly. Furthermore, quantitative measurements support the findings provided by the correlations between probit viability and vigor parameters such as germination percentage (6.56) and the accelerated aging test (7.60). These covariance findings support the idea that these parameters complement each other in predicting seed longevity. Moreover, negative covariance with electrical conductivity (-10.3) supports the idea that seeds with lower electrical conductivity values are those that preserve their membrane stability for a longer period, thus maintaining their vigor and storability (Singh et al. 2016; Prado et al. 2019)

Recent advances in enhancing soybean seed quality are closely aligned with findings on seed longevity and vigor deterioration during storage. Genome editing technologies, specifically CRISPR/Cas9, have significantly improved key seed traits such as protein content, seed size, and coat color, which indirectly boost seed vigor and storability, offering precision breeding tools to optimize seed quality (Sim et al. 2023; Chen et al. 2024). Complementing genetic improvements, seed priming with chemical agents like

carboxymethyl cellulose and Gum Arabic has proven effective in elevating germination rates, seedling root length, and biomass, especially under stress, thereby enhancing seedling vigor and storage resilience (Almakas et al. 2025). Alongside these treatments, the use of airtight packaging combined with moisture control technologies (maintaining seed moisture between 6-8%) mitigates deterioration, preserving seed viability during extended storage periods, as observed in studies on seed moisture management and storage environments (Bharathi et al. 2024). Innovative seed invigoration methods, including magneto-priming, hormonal priming, and bio-priming with plant growth-promoting rhizobacteria, further maintain vigor and enhance stress tolerance (Hozayn et al. 2018; Zalama and Leilah 2019; Sarkar et al. 2021). Additionally, treating soybean seeds with diatomaceous earth, neem seed extract, and silica gel enhances seed storability, reduces insect damage, and improves germination, seedling vigor, and seed yield (Zalama et al. 2024). The integration of these genetic, chemical, and postharvest strategies complements predictive models of seed deterioration, underscoring that both initial seed quality and deterioration rates are critical parameters for effective storage and ensuring high crop performance.

Integrating a simplified viability prediction approach with climate-controlled storage systems can improve prediction accuracy and seed management in diverse environments. Cold storage (15°C and 45% relative humidity) maintains soybean seed quality by reducing deterioration and preserving germination rates, unlike ambient storage (Koskosidis et al. 2022). As temperature and storage time affect seed longevity, combining viability models with controlled storage enhances seed quality monitoring and management (Coradi et al. 2020). This integration minimizes storage losses and supports sustainable crop production and germplasm conservation by ensuring consistent seed performance across varied climates.

In conclusion, this study confirms that the simplified viability equation efficiently and cost-effectively assesses declining soybean seed viability and vigor during ambient storage. Initial seed quality significantly impacts storability, as higher quality seed lots demonstrated longer storage indices, slower deterioration, and greater vigor. Certified seed lots/batches with superior initial quality maintained greater storability and vigor compared to uncertified seeds or those with poorer initial quality,

emphasizing the influence of source, genotype, and initial physiological quality on seed longevity. Combining seed vigor treatments with viability models improves seed warehouse management by predicting seed longevity, identifying at-risk lots, and reducing storage losses. This approach, vital for short- to medium-term seed storage, enhances seed quality, germination, and seedling establishment. By integrating vigor testing, treatments, and modeling, managers can better prevent deterioration, improve stand establishment, and ensure consistent crop performance and yield stability, supporting robust seed lots and greater agricultural productivity. Future research should integrate the predictive viability models with climate-controlled storage systems to enhance the precision of seed longevity predictions and optimize seed management across diverse environmental conditions, thereby supporting sustainable crop production and effective germplasm conservation.

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