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Effects of Fruit Maturity Stage and Seed Storage Conditions on Germination and Endogenous ABA and GA Levels in *Solanum torvum*

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Abstract

Solanum torvum is an important medicinal and culinary vegetable with poor seed propagation, characterized by low germination and limited seed longevity. This study examined the effects of fruit maturity stage, storage temperature, duration, and endogenous hormonal profiles on seed germination. Fruits were harvested at three physiological maturity stages: matured green, ripe yellow, and overripe brown. Extracted seeds were stored in ambient (24–26 °C) and cold (3–8 °C) conditions for 24 weeks, with subsequent germination testing with 3 replicates per treatment. Endogenous abscisic acid (ABA) and gibberellic acid (GA) were quantified using HPLC-DAD to assess their association with germination behaviour. Seeds from ripe yellow fruits achieved the highest germination (95%), with a mean germination time of 12 days and a mean germination rate of 8%, identifying this stage as the optimal maturity stage for harvest. While total germination percentage was enhanced by an after-ripening effect during the first 16 weeks of ambient storage, other vigour parameters, including mean germination time and rate and synchronization began to decline thereafter. ABA and GA concentrations displayed treatment-dependent variation across maturity stages and storage conditions, with hormonal trends showing complex associations with dormancy release rather than consistent main effects. These findings indicate that harvesting *Solanum torvum* fruits at the ripe yellow stage and storing seeds under ambient conditions for up to 16 weeks, under the conditions evaluated in this study, provides a practical balance between dormancy alleviation and seed vigour, thereby improving short-term propagation efficiency.

Keywords: *Solanum torvum*; seed germination; physiological maturity; storage environment; biochemical composition; seed dormancy

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1. Introduction

Solanum torvum Sw. commonly known as Turkey berry or Wild Eggplant, is a resilient wild crop in the Solanaceae family, thriving in various climates and soils [1]. It is native to tropical regions of the Americas, but has spread to various parts of the world, including Africa, Asia and the Pacific islands, where it often grows in disturbed areas [2]. This plant serves as a rootstock for garden eggs under reduced soil moisture conditions due to its drought tolerance [3]. The fruits are rich in antioxidants and vitamins. They are utilized in traditional medicine for their anti-inflammatory properties and in culinary dishes for their distinct flavour [4]. The leaves and fruits are known to retain most of their nutrients even after boiling [5].

Seeds of *Solanum* species frequently exhibit dormancy, resulting in low germination rates and poor field establishment [1,6]. This dormancy is typically a physiological phenomenon that is more prevalent in wild species than in cultivated crops [7]. *Solanum* seeds may possess primary dormancy upon detachment from the parent plant or develop secondary dormancy when exposed to unfavourable environmental conditions [8]. The transition to a non-dormant state often occurs gradually during dry storage at room temperature, a process that can span several weeks to months [8]. This optimizes storage parameters, specifically temperature and humidity, is crucial for maintaining seed longevity and ensuring successful germination [9].

Factors such as seed maturation and fruit characteristics affect successful germination [10]. Seed maturity involves physiological and biochemical changes [11] with abscisic acid (ABA) playing a key role, alongside gibberellic acid (GA), cytokinin, and auxin [12,13]. These changes influence seed germination potential.

The low germinability of *Solanum torvum* seeds has been addressed by several methods: (1) chemical treatment by priming in gibberellic acid, potassium nitrate; (2) scarification by scrubbing rough surfaces; (3) the use of leaf protoplasts [1,14]. While these protocols were effective for immediate dormancy breaking, they do not account for the influence of the seed's physiological state at harvest or its biochemical stability during storage. Moreover, most previous studies have focused on single storage conditions and have not incorporated endogenous hormonal measurements to explain variation in dormancy release and germination behaviour [15]. There is, however, a lack of comprehensive studies on the combined effects of fruit maturity stage and storage environment on seed germination and longevity of *Solanum torvum*. This study advances the field by combining these variables with endogenous hormonal profiling, offering a good physiological basis for optimizing conservation strategies and supporting sustainable production. Optimizing maturity stage for seed harvest can streamline the seed production process and contribute to efficient seed management by saving resources for commercialization. Also, farmers and growers can enhance propagation efforts and ensure successful seedling establishment. Furthermore, studying these factors in combination with plant hormones will enhance crop performance. Therefore, this research aimed to: (1) determine the appropriate maturity stage to harvest seeds; (2) determine the appropriate seed storage temperature and duration; and (3) determine the role of ABA and GA content on the germination of *Solanum torvum*. Such information will contribute to the successful large-scale production of this vegetable through the provision of good-quality seeds with a long shelf life for continuous commercialization.

2. Materials and Methods

2.1. Seed Multiplication and Experimental Design

The study involved a field multiplication of seeds of *Solanum torvum* fruits collected from the wild in the Greater Accra region. Standard agronomic practices (irrigation, pruning, weed and pest control) were used for the multiplication at the West Africa Centre for Crop Improvement (WACCI) research field (5°39′38.1″ N 0°11′26.9″ W) at the University of Ghana farm, Legon, Ghana, and harvested at different maturity stages for the experiment.

The experiment was designed using a completely randomized design with three factors (maturity stage, storage environment and duration) with three replicates for each treatment combination. This totalled seventy-two treatment samples (3 maturity stages × 2 storage environment × 4 storage duration × 3 replicates).

The three distinct maturity stages were selected to represent key physiological milestones: (1) Matured green (83 days after bud initiation (DAB))—this stage marks the completion of the seed-filling phase, where seeds first acquire desiccation tolerance; (2) Ripe yellow (100 DAB)—this stage marks the physiological maturity in *Solanum* species where

dry weight is maximized; and (3) Overripe brown (121 DAB)—this stage was included to examine the effects of extended on-plant maturation on the induction of secondary dormancy common in wild *Solanum* species. These maturity stages were selected after a preliminary study based on repeated tagging and monitoring of flowering plants until consistent external colour transitions and seed germinability were achieved. Seeds were harvested from multiple randomly selected plants and pooled by maturity stage prior to seed extraction to minimize plant-to-plant variability.

Harvested seeds were spread in a single layer on a laboratory bench to ensure uniform natural airflow and dried at ambient temperature (24–26 °C) with an average relative humidity of 50%. The moisture content was determined using the oven-dry method. Five samples from each maturity stage, each weighing 2 g of seeds, were transferred to a previously dried and weighed crucible. The crucible was placed into an oven, and the sample dried overnight at 105 °C. The sample was cooled in a desiccator and then weighed. The moisture content was expressed in weight percentage by measuring weight loss after drying. The drying process lasted three days until the seeds recorded moisture contents between 8.0 and 8.4% (wet basis). Following this, seeds were stored under ambient temperature (24–26 °C) and cold storage (3.2–8 °C) for 8, 16, and 24 weeks. Relative humidity for cold and ambient storage conditions ranged from 67 to 82% and 34 to 62%, respectively. Seeds sown immediately after drying served as the control treatment.

2.2. Seed Viability Assessment

A preliminary viability check was conducted on a representative sample of 100 seeds (two replicates of 50) for all fruit maturity stages (matured green, ripe yellow and overripe brown) using the topographical tetrazolium (TZ) test. Seeds were pre-conditioned by soaking in distilled water for 18 h, bisected longitudinally, and immersed in a 1.0% 2,3,5-triphenyl tetrazolium chloride solution for 24 h at 30 °C in darkness. Viability was determined based on the characteristic red staining of the embryo tissues. Seeds with a completely and uniformly stained pink to bright red embryo were considered viable. Seeds with unstained (white) embryos, patchy or weak staining on vital structures, or those exhibiting flaccid, necrotic tissue in more than 50% of the embryo area were considered non-viable [15].

Seed Germination Test

A preliminary trial was conducted in a germinator at a constant temperature of 25 °C under a 12 h light regime; however, no germination was observed. Hence, germination test was conducted under field conditions, research [16] has shown that many wild Solanum species, including *Solanum torvum*, require fluctuating diurnal temperatures to break dormancy. Also, field germination conditions reflect a typical farmer's environment, thereby enhancing the practical relevance and potential adoption of the findings, given the limited accessibility of controlled growth chambers in local production systems. Therefore, germination tests were conducted under natural field conditions to ensure biologically realistic temperature variation.

Germination tests were conducted by sowing 50 seeds in a 50-cell tray with potting mix (cocopeat, pH of 5.5 to 6.8). The trays were placed in an unshaded field location under natural light conditions (approximately 12 h photoperiod). The environment was characterized by alternating diurnal temperatures ranging from a daytime maximum of 27 °C to a nighttime minimum of 23 °C, with relative humidity fluctuating between 40% and 73%. Each of the twenty-four treatment combinations was replicated three times, and seed emergence was monitored daily for 30 days to give the seeds enough time to germinate.

2.3. Abscisic Acid (ABA) and Gibberellins (GA) Extraction

An extraction solvent consisting of 80% methanol and 1% acetic acid in distilled water was prepared to facilitate the extraction of bioactive compounds (GA and ABA) from *Solanum torvum* seeds. 20 mg of milled *Solanum torvum* seeds were weighed and placed in a 2 mL Eppendorf tube. 1 mL of the extraction solvent was added, followed by vortexing for 10 s to ensure thorough mixing. The sample-solvent mixture was then subjected to sonication for 45 min using an ultrasound bath, which aided in disrupting cell walls and releasing intracellular compounds. The sample was subsequently centrifuged at 21,130× *g* for 10 min to separate the solid residue from the extracted liquid. The supernatant, containing the extracted compounds, was transferred to a 4 mL brown vial for storage. A second extraction step was performed using the same procedure on the remaining pellet to maximize compound recovery. The combined supernatants from both extractions were stored at −15 °C until further analysis. The solid-phase extraction process subjected the extraction to further purification and enrichment procedures.

2.3.1. Solid-Phase Extraction Procedure (SPE)

Following the method described by [17], ABA and GA were extracted from the *Solanum torvum* seeds. The freeze-dried extract was purified using an Oasis HLB 3 cc (60 mg) cartridge (Oasis HLB 3 cc Vac Cartridge, 60 mg sorbent; Waters Corporation, Milford, MA, USA). The cartridge was preconditioned with 4 mL of methanol (100%), 4 mL of bi-distilled water, and 4 mL of 20% methanol solution at pH 3. The dissolved extract was passed through the sorbent, then washed with 4 mL of bi-distilled water, and the retained plant growth regulators were eluted with 2 mL of methanol. The eluate was then filtered through a 0.45 µm membrane. This procedure was repeated three times for each seed sample.

2.3.2. HPLC Analysis

High-performance liquid chromatography with diode-array detection (HPLC-DAD) was used for the quantification of abscisic acid (ABA) and gibberellic acid (GA).

To prepare the standard solutions, 10 mg of each standard, ABA and GA, were dissolved in 10 mL of HPLC-grade methanol to obtain stock solutions. Serial dilutions of these stock solutions were performed using volumetric flasks and micropipettes to generate a range of known concentrations. For ABA, a 1 mg/mL stock solution was diluted to obtain 0.1, 0.2, 0.5, 1, 2, 5, and 10 µg/mL solutions. Serial dilutions were also performed to obtain concentrations of 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, and 30 µg/mL for GA. Standards and seed extracts were centrifuged at 16,000× *g* for 10 min before analysis, and supernatants were transferred into HPLC vials.

Chromatographic separation was performed on an Agilent 1290 Infinity II HPLC system (Agilent Technologies, Waldbronn, Germany) equipped with a Discovery C18 column (125 mm × 3 mm, 5 µm particle size; Supelco, Bellefonte, PA, USA) coupled to an Agilent 1260 Infinity II diode-array detector (Agilent Technologies, Waldbronn, Germany). Isocratic elution was carried out using solvent A (0.1% formic acid in distilled water) and solvent B (100% methanol) at a flow rate of 0.8 mL min^{-1} and a total run time of 30 min.

For standard calibration, solvent ratios of A:B = 80:20 and 70:30 (*v*/*v*) were evaluated to optimize separation. Under the final working conditions (A:B = 70:30), GA and ABA eluted at approximately 4.5 min and 10.7 min, respectively.

To account for matrix interference in seed extracts, quantification was performed using the standard-addition method. Aliquots of each sample extract were spiked with known volumes of ABA and GA standards, and endogenous hormone concentrations were calculated from the increase in peak area relative to unspiked samples.

Detection was carried out at 208 nm. Hormones were identified based on retention time matching with analytical standards and confirmed by peak enhancement following spiking. The peak areas of the analytes were recorded and quantified using a linear regression model. Calibration curves for ABA and GA showed high linearity of $R^2 = 0.9968$ and $R^2 = 0.9998$, respectively, over the concentration range tested (Figure 1). Due to the absence of isotopically labelled internal standards, hormone concentrations were reported as relative estimates suitable for comparative analysis among treatments rather than absolute endogenous values.

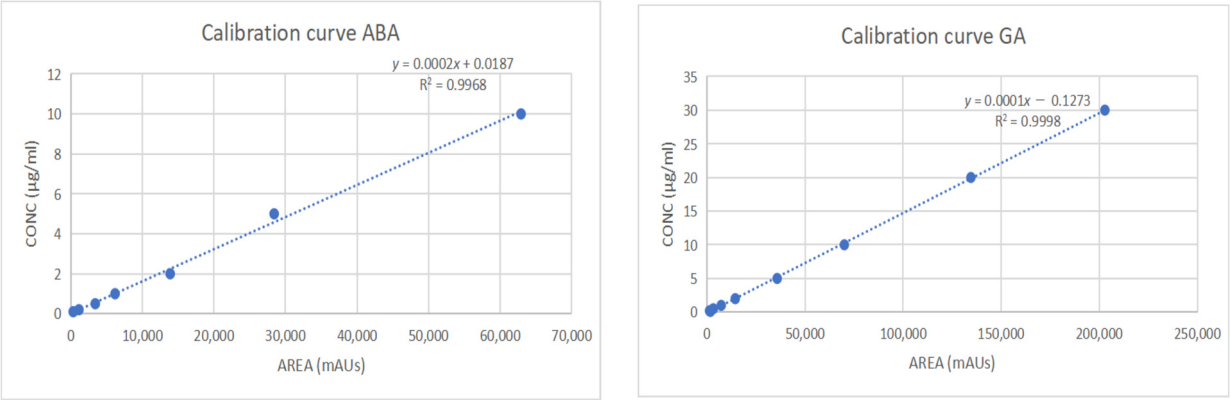

Figure 1. Calibration curve of Abscisic acid (ABA) and Gibberellic acid (GA).

2.4. Data Analysis

The germination parameters were analyzed using a formulated Excel spreadsheet [18]. All statistical analyses were performed using R programming (version 4.3.3) within the RStudio environment (version 4.3.3). Before analysis, the data were screened for the underlying assumptions of linear models. Normality of residuals was assessed using the Shapiro–Wilk test, and homogeneity of variances was evaluated using Levene's test. For parameters which did not meet the requirement of normality, a Generalized Linear Model (GLM) was used.

Germination percentage was analyzed using a generalized linear model (GLM) with binomial error distribution, while mean germination time, synchronization index (Z), time to 50% germination (T50), abscisic acid (ABA), and gibberellic acid (GA) were analyzed using GLMs with Gaussian error distribution. Mean germination rate was analyzed using three-way ANOVA. Significance of main effects and interactions was assessed using likelihood-ratio Type II tests (car package). *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure.

3. Results

The initial viability of the seed lot, as determined by the tetrazolium test for matured green, ripe yellow and overripe brown, was 72%, 94%, and 92%, respectively. This indicates that the seeds were viable and that subsequent low germination in control treatments was attributable to physiological dormancy.

3.1. Effect of Fruit Maturity Stage, Seed Storage Environment and Duration on Germination Parameters

3.1.1. Germination Percentage (%)

Germination percentage (GP) was significantly influenced by fruit maturity stage (FDR-adjusted $p < 0.001$), storage duration (FDR-adjusted $p < 0.001$), and their interaction (FDR-adjusted $p < 0.001$); however, storage environment had no significant main effect (FDR-

adjusted $p = 0.341$) (Table 1). Germination increased with storage duration across all maturity stages, indicating progressive release of dormancy during after-ripening (Figure 2).

Table 1. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on germination percentage (GP) of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	368.627	2	<0.001	<0.001
Storage Environment	0.908	1	0.341	0.341
Storage Duration	240.665	3	<0.001	<0.001
Maturity Stages × Storage Environment	7.194	2	0.027	0.032
Maturity Stages × Storage Duration	48.494	6	<0.001	<0.001
Storage Environment × Storage Duration	61.572	3	<0.001	<0.001
Maturity Stages × Storage Environment × Storage Duration	45.879	6	<0.001	<0.001

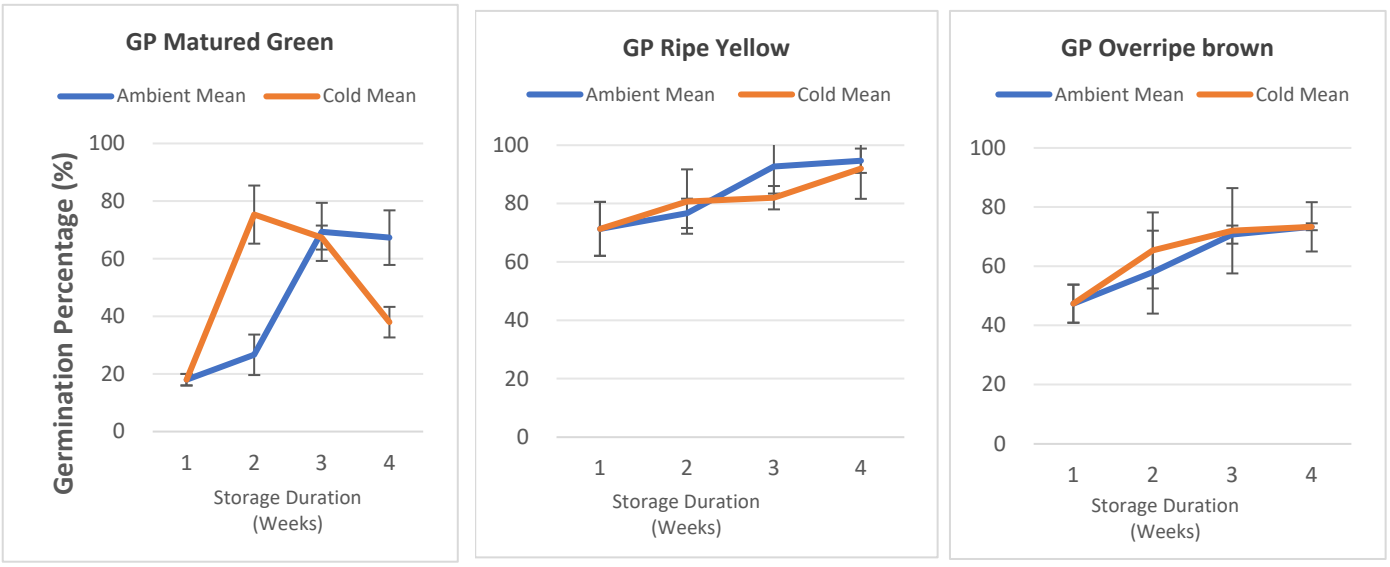

Figure 2. Germination percentage (GP) of *Solanum torvum* seeds as affected by fruit maturity stage, storage environment, and storage duration. Values represent mean ± SD (n = 3).

Seeds harvested at the ripe yellow stage consistently showed the highest germination, reaching a maximum of 95% after 24 weeks of storage. Overripe brown seeds exhibited moderate improvement, attaining 73% germination, while matured green seeds showed the lowest final germination (67%) and greater sensitivity to storage conditions. Notably, germination of matured green seeds declined after 8 weeks under cold storage and after 16 weeks under ambient storage, suggesting a physiological dormancy at harvest (Figure 2).

3.1.2. Mean Germination Time (Days)

Mean germination time (MGT) was significantly affected by fruit maturity stage (FDR-adjusted $p < 0.001$), storage duration (FDR-adjusted $p < 0.001$), and their interaction (FDR-adjusted $p < 0.001$), while storage environment showed no significant main effect (FDR-adjusted $p = 0.978$) (Table 2). Seeds from ripe yellow fruits consistently exhibited the lowest MGT (approximately 12 days), indicating faster germination relative to matured green and overripe seeds (Figure 3).

Table 2. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on mean germination time (MGT) of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	30.815	2	<0.001	<0.001
Storage Environment	0.044	2	0.978	0.978
Storage Duration	191.982	3	<0.001	<0.001
Maturity Stages × Storage Environment	3.264	2	0.196	0.274
Maturity Stages × Storage Duration	42.553	6	<0.001	<0.001
Storage Environment × Storage Duration	8.912	3	0.030	0.053
Maturity Stages × Storage Environment × Storage Duration	4.955	5	0.421	0.492

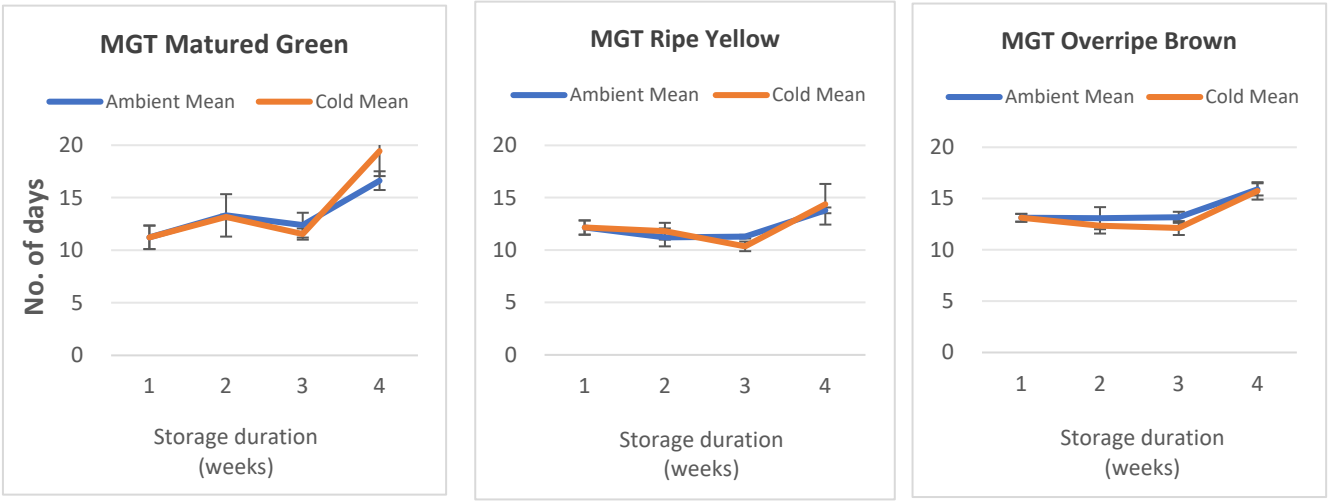

Figure 3. Mean germination time (MGT) of *Solanum torvum* seeds under different fruit maturity stages, storage environments, and storage durations. Values represent mean ± SD (n = 3).

Across treatments, MGT declined with increasing storage duration, reflecting accelerated germination following after-ripening. However, a transient increase at 16 weeks was observed across maturity stages, suggesting a temporary slowing of germination prior to further dormancy release by 24 weeks.

3.1.3. Mean Germination Rate (% of Seeds per Day)

The Mean Germination Rate (MGR), representing the daily percentage of the seed population that germinates, was significantly influenced by maturity stage (F $p < 0.001$) and storage duration (F $p < 0.001$), whereas storage environment had no significant effect (F $p = 0.501$) and their interaction (F $p = 0.824$) (Table 3).

Seeds from ripe yellow fruits exhibited the highest MGR with a daily average of 8% of seeds germinating per day, indicating the most rapid germination compared to matured green and overripe seeds. Consistent with the fluctuations observed in MGT, Figure 4 shows a distinct decline in MGR for all treatments starting after 16 weeks of storage. This "dip" in the graph indicates a synchronized slowdown in germination speed across both ambient and cold storage environments before final measurements were taken at 24 weeks.

Table 3. Analysis of variance (ANOVA) showing the effects of fruit maturity stage, storage environment, storage duration, and their interactions on mean germination rate (MGR) of *Solanum torvum* seeds.

Source of Variation	df	Sum of Squares	Mean Squares	v.r.	F*pr.*
Maturity Stages	2	0.00106136	0.00053068	17.18	<0.001
Storage Environment	1	0.00001422	0.00001422	0.46	0.501
Storage Duration	3	0.005229	0.001743	56.43	<0.001
Maturity Stages × Storage Environment	2	0.00004686	0.00002343	0.76	0.474
Maturity Stages × Storage Duration	6	0.00113975	0.00018996	6.15	<0.001
Storage Environment × Storage Duration	3	0.00023922	0.00007974	2.58	0.064
Maturity Stages × Storage Environment × Storage Duration	6	0.00008803	0.00001467	0.47	0.824
Total	71	0.00930111			

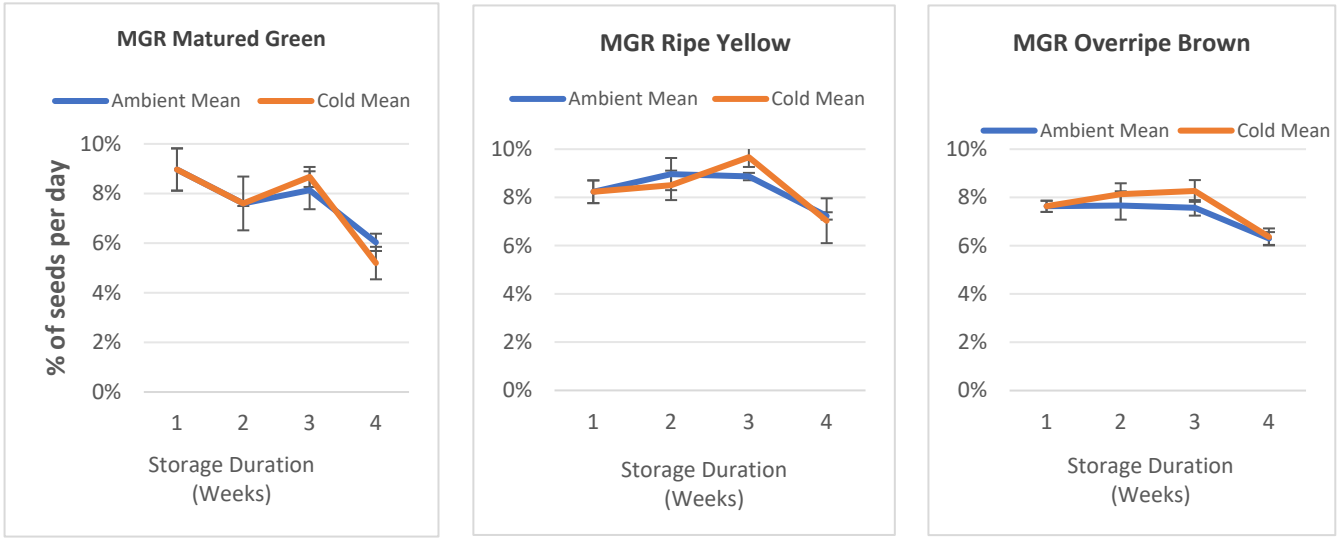

Figure 4. Mean germination rate (MGR) of *Solanum torvum* seeds under different fruit maturity stages, storage environments, and storage durations. Values represent mean ± SD (n = 3).

3.1.4. Synchronization Index (Z)

The Synchronization Index (Z), which quantifies the uniformity of germination timing, was significantly affected by maturity stage (FDR-adjusted $p < 0.002$), whereas storage environment (FDR-adjusted $p = 0.141$), storage duration (FDR-adjusted $p = 0.082$), and their interaction (FDR-adjusted $p = 0.373$), had no significant effect (Table 4).

Table 4. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on synchronization index (Z) of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	16.820	2	<0.001	0.002
Storage Environment	5.044	2	0.080	0.141
Storage Duration	9.503	3	0.023	0.082
Maturity Stages × Storage Environment	1.973	2	0.373	0.373
Maturity Stages × Storage Duration	12.885	6	0.045	0.105
Storage Environment × Storage Duration	3.428	3	0.330	0.373
Maturity Stages × Storage Environment × Storage Duration	6.083	5	0.298	0.373

The ripe yellow seeds recorded the highest mean Z value (0.19), indicating the highest degree of synchrony. While Z values for overripe brown and mature green seeds remained relatively stable before dropping after 16 weeks, the synchronization for overripe fruits began to decline much earlier, at 8 weeks of storage (Figure 5). Although storage environments did not show significant variance between maturity stages, the graph reflects slightly higher Z values for ambient storage compared to cold storage. This suggests that ambient temperatures may promote a more uniform release from dormancy than refrigerated conditions.

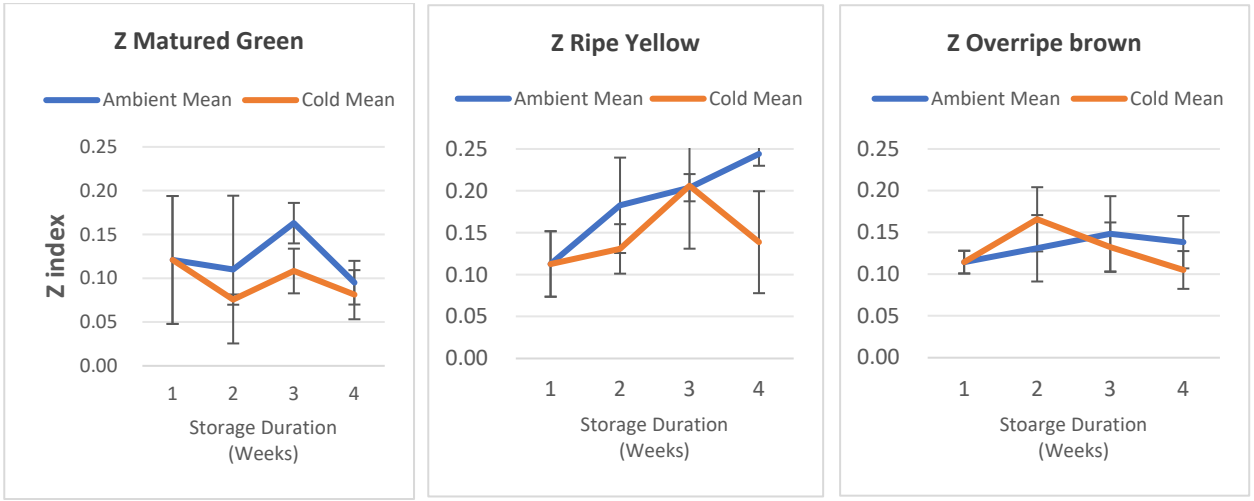

Figure 5. Synchronization index (Z) of *Solanum torvum* seeds in response to fruit maturity stage and storage conditions. Values represent mean ± SD (n = 3).

3.1.5. Time to 50% Germination

Time to 50% germination was significantly influenced by maturity stage (FDR-adjusted $p < 0.001$) and storage duration (FDR-adjusted $p < 0.001$), whereas storage environment had no significant effect (FDR-adjusted $p = 0.999$) and their interaction FDR-adjusted $p = 0.179$) (Table 5).

Table 5. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on time to 50% germination (T50) of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	20.275	2	<0.001	<0.001
Storage Environment	0.003	2	0.999	0.999
Storage Duration	173.077	3	<0.001	<0.001
Maturity Stages × Storage Environment	4.052	2	0.132	0.179
Maturity Stages × Storage Duration	59.890	6	<0.001	<0.001
Storage Environment × Storage Duration	12.987	3	0.005	0.008
Maturity Stages × Storage Environment × Storage Duration	8.047	5	0.154	0.179

Across treatments, T50 decreased with increasing storage duration for ripe yellow and overripe brown, taking an average of 11 and 12 days, respectively, to reach 50% germination. This indicates the most rapid germination (Figure 6). However, an increase at 16 weeks was observed across maturity stages, slowing germination. Seeds stored under ambient conditions did not differ from cold conditions.

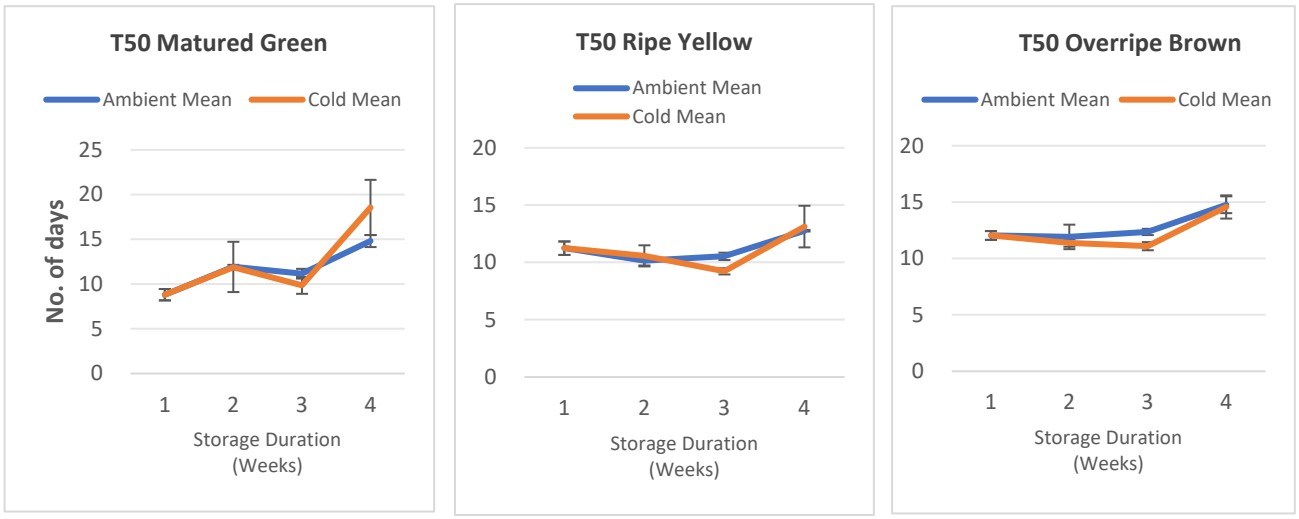

Figure 6. Time to 50% germination (T50) of *Solanum torvum* seeds across fruit maturity stages and storage conditions. Values represent mean ± SD (n = 3).

3.1.6. Abscisic Acid (ABA) and Gibberellic Acid (GA)

Abscisic acid (ABA) concentrations showed a significant three-way interaction among fruit maturity stage, storage environment, and storage duration (FDR-adjusted $p < 0.004$; Table 6), indicating that ABA responses varied depending on the combined effects of developmental stage and storage conditions. No significant main effects of maturity stage, storage environment, or storage duration were detected after FDR correction (FDR-adjusted $p > 0.05$).

Table 6. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on abscisic acid (ABA) content of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	5.234	2	0.073	0.115
Storage Environment	5.459	2	0.065	0.115
Storage Duration	6.705	3	0.082	0.115
Maturity Stages × Storage Environment	2.181	2	0.336	0.392
Maturity Stages × Storage Duration	14.754	6	0.022	0.078
Storage Environment × Storage Duration	2.970	3	0.396	0.396
Maturity Stages × Storage Environment × Storage Duration	21.709	5	0.001	0.004

Overripe brown seeds exhibited the highest initial ABA levels (approximately 0.23 µg g^{-1}), followed by mature green seeds (≈0.16 µg g^{-1}), whereas ripe yellow seeds showed the lowest initial concentrations (≈0.13 µg g^{-1}) (Figure 7). ABA levels fluctuated during storage, with patterns differing across maturity stages and storage environments, consistent with significant three-way interaction.

For gibberellic acid (GA), although raw *p*-values suggested effects of maturity stage and storage duration, none of these effects remained significant following FDR adjustment (Table 7). Mature green seeds exhibited higher initial GA concentrations (≈0.5 µg g^{-1}) compared with ripe yellow and overripe brown seeds (≈0.2 and 0.3 µg g^{-1}, respectively) (Figure 8). GA concentrations generally declined during storage; however, these trends were highly variable and did not reach statistical significance after FDR correction.

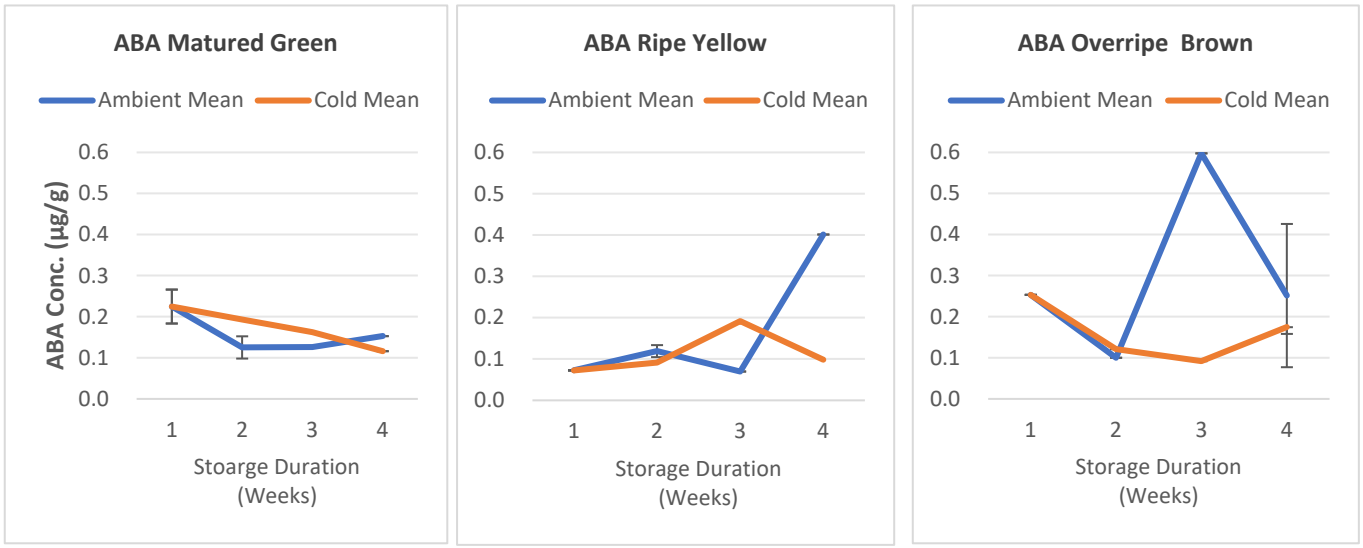

Figure 7. Abscisic acid (ABA) content of *Solanum torvum* seeds as influenced by fruit maturity stage, storage environment, and storage duration. Values represent mean ± SD (n = 3).

Table 7. Likelihood-ratio tests (Type II GLM) for the effects of fruit maturity stage, storage environment, storage duration, and their interactions on gibberellic acid (GA) content of *Solanum torvum* seeds. *p*-values were adjusted using the Benjamini–Hochberg false discovery rate (FDR).

Effect	LR χ^2	df	Raw *p*-Value	FDR *p*-Value
Maturity Stages	9.067	2	0.011	0.075
Storage Environment	0.712	2	0.701	0.817
Storage Duration	8.557	3	0.036	0.084
Maturity Stages × Storage Environment	1.952	2	0.377	0.660
Maturity Stages × Storage Duration	14.295	6	0.027	0.084
Storage Environment × Storage Duration	0.316	3	0.957	0.957
Maturity Stages × Storage Environment × Storage Duration	3.708	5	0.592	0.817

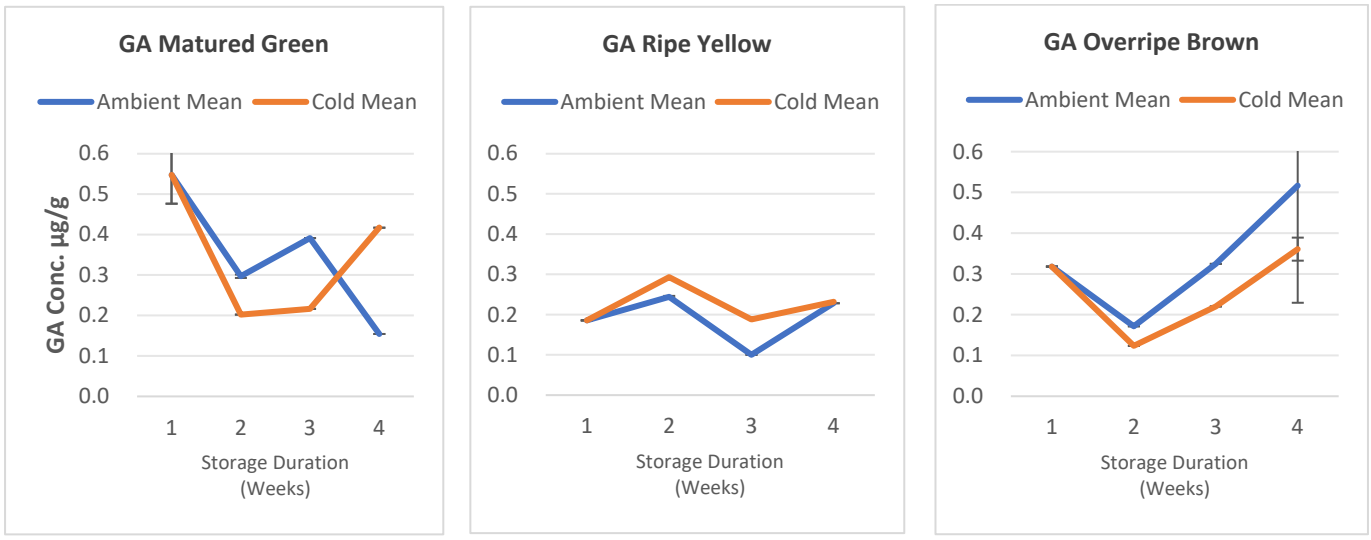

Figure 8. Gibberellic acid (GA) content of *Solanum torvum* seeds during storage across fruit maturity stages. Values represent mean ± SD (n = 3).

ABA and GA levels displayed complex and treatment-dependent patterns during storage. These hormonal profiles were associated with the germination responses reported

earlier, but due to analytical limitations and the absence of internal standards, hormone concentrations are interpreted comparatively rather than as direct regulatory measures.

4. Discussion

4.1. Optimal Maturity Stage of Harvesting Solanum torvum Fruits for Quality Seed Production

The results show that seeds harvested at the ripe yellow stage exhibited the highest germination percentages throughout the storage duration, reaching 95%. This is associated with the accumulation of essential reserves for germination [19] and the natural release of the physiological dormancy (PD) through after-ripening during the maturation process [14,20,21]. Many species in the Solanaceae family, including *Solanum torvum*, are characterized by this endogenous dormancy type, where metabolic requirements for germination are met only after exposure to specific environmental or hormonal cues. In contrast, mature green seeds were less viable, which can be attributed to both incomplete development and deep levels of primary physiological dormancy typical of immature embryos in this genus [22]. Overripe seeds also exhibited reduced viability, likely due to ageing and delayed harvest stress, which has been associated with dormancy cycling in some *Solanum* species [23]. Beyond germination percentage, the ripe yellow stage facilitated faster and more uniform germination, supporting consistent and efficient seedling emergence in the field [24].

The study indicates that maturity stages, associated with fruit colour, are essential for determining the optimal harvest stage of *Solanum torvum* seeds. A similar indication has been observed in African eggplant and *Jatropha curcas* [25,26], where yellow or yellow-green fruits yielded the highest germination rates. Thus, harvesting *Solanum torvum* seeds at the ripe yellow stage is optimal for achieving high germination success.

4.2. Interaction of Storage Temperature and Duration on Germination and Longevity of Solanum torvum Seeds

Seeds stored at ambient temperatures (23–26 °C) showed higher germination percentages than those stored in cold conditions (4–8 °C), especially for seeds from ripe yellow fruits. This aligns with research indicating that warmer temperatures boost metabolic activity and enzyme function in seeds, leading to faster germination [27,28]. Cold storage can be beneficial for long-term seed preservation in some species; however, its effects on *Solanum torvum* were variable: it improved germination of overripe seeds but reduced performance in mature green seeds at longer storage durations. This response may reflect delayed dormancy alleviation under low temperatures [20,27] rather than outright loss of viability, and the possibility of chilling injury cannot be excluded [29]. Conversely, low temperatures may slow the natural rate of deterioration in overripe seeds, helping to maintain viability for longer periods relative to ambient conditions. However, this finding does not suggest that ambient storage is superior for long-term seed conservation; rather, it reflects a short-term physiological response associated with dormancy release in freshly harvested seeds of *Solanum torvum* under the specific storage durations evaluated in this study.

Solanum torvum exhibited increased germination rates with extended storage, possibly due to the occurrence of temperature-sensitive after-ripening effects. This physiological transition is common among Solanaceae, such as *Solanum melongena*, where an initial storage period under ambient conditions is often required to overcome primary physiological dormancy [24]. However, the kinetics of this dormancy release are highly species-specific; while some related taxa maintain viability for extended periods, the rate of after-ripening in *Solanum torvum* is uniquely governed by the interaction between seed maturity at harvest and storage temperature [20]. In this study, the absence of consistent main effects across all

maturity stages suggests that the thermal requirements for optimal dormancy dissipation vary depending on the initial depth of dormancy at the time of harvest.

Abscisic acid (ABA) concentrations displayed treatment-dependent variation, with a significant three-way interaction among maturity stage, storage environment, and storage duration. Mature green seeds exhibited higher initial ABA levels than ripe yellow seeds, consistent with the association of ABA with dormancy maintenance reported in previous studies [12,19]. However, no significant main effects of ABA were detected after FDR correction, indicating that ABA responses were context-dependent rather than uniform across treatments. Gibberellic acid (GA) levels showed high variability, and none of the observed trends remained statistically significant following FDR adjustment. Although GA is widely implicated in promoting germination [30,31] the present results suggest that GA concentration alone was not predictive of germination performance under the analytical conditions employed. Collectively, ABA and GA profiles exhibited complex patterns that were associated with germination behaviour; however, due to analytical limitations and the absence of internal standards, hormonal concentrations are interpreted comparatively rather than as direct regulatory measures.

5. Conclusions

Seeds from ripe yellow *Solanum torvum* fruits (100 DAB) exhibited the highest viability and vigour, identifying this stage as optimal for seed production. Within the 24-week scope of this study, storage at ambient conditions (24–26 °C) facilitated the highest germination percentages, particularly for ripe yellow seeds. Specifically, germination percentage for matured green seeds declined to 16% after 16 weeks, while ripe yellow and overripe brown seeds increased by 6% and 2%, respectively, suggesting a short-term after-ripening effect. However, despite improved germination percentages, vigour parameters, including mean germination rate (MGR) and synchronization index (Z), declined beyond 16 weeks.

Accordingly, to balance dormancy release with seed vigour, it is recommended that seeds from ripe yellow fruits be stored at ambient temperature in sealed containers and sown within approximately 16 weeks under conditions similar to those of this study. Seed performance in *Solanum torvum* reflects a complex interaction between maturity stage and storage environment. Although ABA and GA levels varied across treatments, no consistent hormonal pattern was observed, highlighting the need for further research incorporating hormonal metabolism, gene expression and moisture uptake dynamics to better characterize long-term storage behaviour in this species.

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