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RESEARCH ARTICLE

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Optimizing Chia (Salvia hispanica L.) Seed Germination: Effects of Thermal and Seed Aging on Physiological Parameters-a Case Study from Western Morocco

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ABSTRACT

This study provides a thorough examination of the germination properties of chia seeds (*Salvia hispanica L.*) grown for the first time in Western Morocco, with particular emphasis on thermal stress and the influence of seed aging. Two trials were performed: i) temperature response with seeds recently harvested (2025), examining four temperatures (16,19,26, and 35°C; 20 seeds × 5 replications; counted daily for 8 days), and ii) the longevity of seeds across 4 generations at 26°C (G1:2022, G2:2023, G3:2024, G4:2025). Eight physiological germination traits were quantified, including germination speed (8.05–9.63 day^{-1} at optimal temperatures), vigor (73.0–100.0%), final germination percentage (100.0%), median germination time (1.0–2.0 days), mean germination time (1.00 ± 0.00 to 3.04 ± 0.44 days), mean germination rate (0.065–0.125 day^{-1}), daily germination speed (1.00 ± 0.00 to 0.265 ± 0.034 day^{-1}), and mean time to germination. Temperature had a marked influence on germination performance. The optimum temperature was 26°C, yielding 100% germination and the highest speed and vigor. In contrast, exposure to 35°C substantially reduced final germination (52.0 ± 7.58%) and vigor (28.0 ± 2.74%), indicating thermal inhibition at supra-optimal temperatures. Seed aging also had a pronounced impact. Seed aging had a major impact: the most recent lot (G4–2025) germinated rapidly (mean 1.00 ± 0.00 days; Daily Germination Speed 0.990 ± 0.022 days; vigor 99.0 ± 2.23%), whereas the oldest lot (G1–2022) was slower (mean 2.98 ± 0.22 days; vigor 61.0 ± 15.57%). ANOVA confirmed highly significant effects for both temperature ($F = 1226.39$, $P<0.001$) and seed generation ($F = 321.28$, $P<0.001$) on all traits. Accordingly, this multi-parameter study suggests that moderate sowing temperatures and harvesting seeds that are relatively fresh are critical to high germination success and effective agricultural management of chia in a semi-arid Mediterranean context. These are the first Moroccan data, and will support improvements in agronomy, seed lot modelling, conservation, and valorisation of chia among other priorities relevant to these efforts.

Keywords: Chia (*Salvia hispanica*), Seed viability, Temperature stress, Germination rate, Seed aging, Mediterranean agriculture.

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INTRODUCTION

The agricultural sector is increasingly confronted with abiotic stressors that affect crop establishment and yield, with heat stress being among the greatest risks to seedling vigor and crop production (Del Buono et al., 2021; Mittler et al., 2025). Climate change is impacting Mediterranean agriculture - Morocco is a hot spot for agriculture that relies on warming temperatures and less rainfall as a source for agricultural production (Balaghi, 2024). It is expected that, per the Intergovernmental Panel on Climate Change, the average temperatures in Morocco and the Mediterranean region will increase by an average of +2 to +2.5°C by the year 2050, and droughts and water stress will increase in both frequency and intensity across the region (IPCC, 2022; FAO, 2022). The physiological and quality characteristics of the seeds produced by oilseed crops such as chia (*Salvia hispanica L.*) are highly affected by changes to local climatic conditions. In addition to inducing physiological and biochemical changes in the crop, high temperatures also

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expedite seed aging, resulting in rapid loss of viability and germination success (Riedesel et al., 2024).

Seed aging and thermal stress are significant limitations on germination, viability and productivity of agricultural crops, particularly in Meditteranean climate with an unstable climate. Seed aging is a gradual process that can be speeded up when seeds have been exposed to higher temperatures, causing the seeds to form various molecular changes that affect the physiological quality of seeds adversely (Arif et al., 2022; Xing et al., 2025). Although there are many negative molecular changes that occur as seeds age, it is possible to treat seeds so that those negative molecular changes can be counteracted through seed priming, allowing the seeds to regain their vigor as well as their capacity for germination after they are aged. (Xing et al., 2025). Thus, generating a vigorous seedling stand becomes vital, as seed germination is a major driver of crop performance in terms of yield, resilience, and resource-use efficiency (Benidire et al., 2015; Fahad et al., 2019; Yehia et al., 2024). Thermal modeling of seed germination indicates that rising temperatures can affect seed germination capacity at a rapid rate and will thus affect the ability of crops to regenerate (Correa et al., 2021); accordingly, it is necessary to attain a clear understanding of the relationship between thermal stress, seed ageing, and adaptations such as that of Chia in agricultural systems in Morocco in order to formulate sustainable adaptation strategies in response to current and impending climate-related challenges.

Chia (*Salvia hispanica L.*), an annual herbaceous pseudo-cereal belonging to the Lamiaceae family, has acquired worldwide recognition due to its nutrient density, adaptability to different environments, and presence of health-promoting bioactives including omega-3 fatty acids, minerals, antioxidants, and protein (Mohd Ali et al., 2012; Muñoz et al., 2013; De Falco et al., 2021; Din et al., 2021) , has recently been studied for the variability in physiological quality related to factors such as seed coat color and post-harvest management (Motyka et al., 2023; Silva et al., 2024). Its production is emerging in new climates, including the Mediterranean, due to trends in diet and demands for diversification (Stefanello et al., 2022; Sampayo-Maldonado et al., 2025). Chia Seeds are a great option for increasing agricultural diversity and resiliency in regions impacted by climate change because they are well-adapted to the Mediterranean climate of Morocco. Several Thermal model studies show that increased temperature may decrease the ability of plants to produce viable seeds which could threaten the ability of future generations of crops to establish and grow (Correa et al. 2021). Determining how thermal stress, seed aging and crop adaptation systems interact with each other in the Moroccan agricultural system is critical to ensuring future sustainability of Moroccan food production. Despite the increasing importance of research on chia seed germination in stress conditions, most of the literature related to thermal factor and seed age (time elapsed in storage) remains scarce, especially in Mediterranean environments (Stefanello et al., 2022; Rodríguez et al., 2024; Riedesel et al., 2024). However, from recent proteomic and physiological studies, we know that temperature and seed age will have a strong impact on Salvia hispanica viability, vigor, and rate of emergence (Rodríguez et al., 2024). Specifically, high temperature and long durations of storage will cause biochemical changes and protein degradation resulting in substantial loss of the germination potential (Yehia et al., 2024). The effect on germination not only influences establishment in the field; it will also affect agro-industrial quality and yield.

By combining data regarding seed longevity, the physiological aspects of the plants, and the environmental forecasts for Morocco, this research is being conducted to evaluate how much of an effect thermal stress and the changing climate would have on Medina Area Agricultural Systems' seed germination ability and quality. To fill these gaps, the study presented here is to assess for the first time how temperature regimes (16, 19, 26, and 35°C) and seed age (1-4 years in storage) affect eight physiological germination traits in Mediterranean climates. The use of four consecutive harvests, daily observations, and multivariate analysis provides new perspectives on the mechanisms of chia seed viability and opens avenues for agronomic practices that are optimized for the region.

MATERIALS & METHODS

Seed Material

The chia (*Salvia hispanica L.*) seeds used in this study were obtained from experimental plots in western Morocco (Gharb region), harvested each summer between 2022 and 2025 following the methodology of Rossafi et al. (2025). All germination trials used seeds produced according to this methodology and conditioned under controlled ambient conditions at the Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco.

Study Area

In Northwestern Morocco (North Coast, Mediterranean Area), Rabat, Salé, Kenitra, and the Gharb Plain were studied for abiotic and biotic effects on Chia Seeds (Salvia hispanica L.) in terms of the field and Laboratory Analysis of Germination. The research for this project was conducted at the Faculty of Sciences of Ibn Tofail University in Kenitra, Morocco (34.24573°N, 6.58878°W). This region is noted for its fertile soils, mild, wet winters and hot, dry summers. The Gharb Plain is characterized as an Area with an Alluvial Soil consisting of limited input from high temperatures and climatic stress on crops such as Chia. Fig. 1 indicates that the conditions of the Gharb Plain are Ideal for studying the influence of climate on crop germination.

Experimental Site and Germination Protocol

The experiments were carried out at the Laboratory of Natural Resources and Sustainable Development, Faculty of Sciences, and university of Kenitra. Emergency seeds were surface sterilized using a 2% sodium hypochlorite solution for 7 minutes followed by rinsing using sterile distilled water. Seeds (100 seeds per treatment—5 replications of 20 seeds each) were placed on two layers of Whatman No.1 filter paper in 10 cm Petri dishes and moistened with sterile distilled water, following standard procedures recommended by the International Seed Testing Association

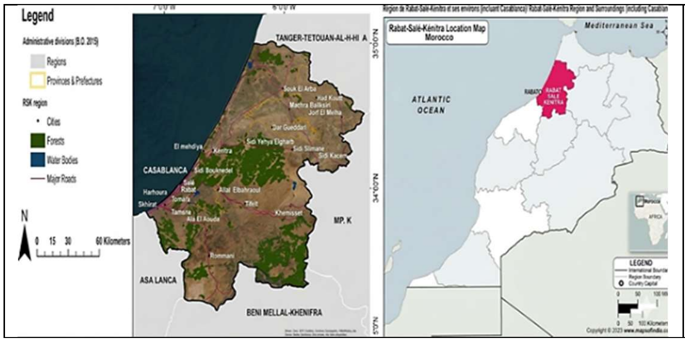

Fig. 1: Location map of the Rabat-Salé-Kénitra region, Morocco. Map created by the author using online cartographic resources.

(ISTA, 1999). Petri dishes were capped and incubated in the dark at constant temperatures (16, 19, 26, or 35°C) in order to assess the temperature on germination. To assess seeds exposed to aging, all seeds from the harvest years of 2022, 2023, 2024, and 2025 were evaluated at 26°C and these tests were conducted to test for any significant differences that would indicate a seed age difference in germination. Germination was determined by radicle emergence (minimum of 2 mm). Germinated seeds were counted and removed daily for 8 consecutive days.

Data for Germinated: Measurements

The following physiological parameters were measured and calculated for all replicates, using established formulas (Maguire, 1962; ISTA, 1999; Larsen & Andreasen, 2004; Kader, 2005; Hajlaoui et al., 2007; Oukara et al., 2017; Younis et al., 2021):

- Germination Percentage (GP):

$$GP = \frac{\text{Number of germinated seeds}}{\text{Number of sown seeds}} \times 100$$

- Germination Kinetics (GK):

Number of seeds germinated at 24, 48, 72, and 96 h after onset (Hajlaoui et al., 2007).

- Germination Speed (GS):

Measures the rapidity and uniformity of germination; calculated as described in Maguire (1962).

- Median Germination Time (T50):

Number of days required for 50% of seeds to germinate; estimated graphically/interpolated from cumulative germination data (Larsen & Andreasen, 2004).

- Mean Germination Rate (MGR):

The reciprocal of mean germination time: $\text{MGR} = \frac{1}{\text{MTG}}$ (germinations/day).

- Mean Germination Time (MTG):

$MTG = \frac{\sum(n \times d)}{\sum n}$, where n is the number of newly germinated seeds at day d (ISTA, 1999; Kader, 2005).

- Germination Vigor Index (GVI):

Sum of [number of normal seedlings counted]/[days to respective counts] across evaluation days.

- Daily Germination Speed (DGS):

Indicates vigor/quality as per Maguire (1962): $DGS = \sum \frac{n}{d}$, with n the number of seeds germinated on day d.

Statistical Analysis

All tests were performed with five replicates per condition for both temperature and generation assays. Results for each parameter are reported as mean ± SD. Statistical analyses included one-way ANOVA to determine the significance of temperature or generation on germination parameters, followed by Tukey's post hoc test ($P<0.05$) to identify statistically different groups (Zar, 2010; Younis et al., 2021). All analyses were performed using using SPSS software (version 23, IBM Corp).

RESULTS

The germination performance of chia (Salvia hispanica L.) seeds was strongly influenced by both temperature and seed age.

Presentation of All Major Physiological Germination Parameters Measured in this Study

Temperature Effect

Germination was highest at 16°C, 19°C and 26°C, reaching 100% emergence with high germination speeds: 8.05 ± 0.48day^{-1}, 9.63 ± 0.13day^{-1} and Mean Germination Rate 0.125 ± 0.000 day^{-1}. Germination Vigor ranged from 73.0 ± 13.51% (16°C) to 100.0 ± 0.0% (26°C), while it dropped sharply at 35°C (28.0 ± 2.74%). The mean germination time and median germination are significantly shorter at 26°C (1.00 ± 0.00 days). ANOVA and Tukey analyses confirm that high temperatures (35°C) reduce viability, speed and regularity of germination ($P<0.001$). (Table 1).

Effect of Generation/year

At 26°C, the most recent generation (G4–2025) exhibits almost instantaneous germination (Mean_germination 1.00 ± 0.00 days, DGS 0.990 ± 0.022day^{-1}), maximum vigour (99.0 ± 2.23%) and the highest speed (8.72 ± 0.31day^{-1}). Older batches (G1–2022, G2–2023) show a slowdown and a decrease in vigour (Germination_vigor 61.0 ± 15.57% to 85.0 ± 3.53% depending on the year). For each parameter, the differences between generations are validated by ANOVA and Tukey ($P<0.05$). (Table 2).

Germination percentage (GP)

Germination percentage is a key indicator of overall seed viability and reflects the proportion of seeds that successfully initiate growth. High rates indicate strong physiological health, while declines reveal stress effects or seed aging. As shown in Fig. 2, at 16°C, 19°C, and 26°C final germination rates are 100%. However, at a temperature of 35°C, the final germination rate is noticeably lower translated to 52%. As shown in Fig. 3, germination rates are seen to incrementally increase across generations of

Table 1: Physiological germination parameters of chia seeds at different incubation temperatures (mean ± SD, n=5)

Parameters	16°C	19°C	26°C	35°C	F-value	p-value
Germination_speed (1/day)	8.05 ± 0.48b	9.63 ± 0.13a	1.00 ± 0.00d	2.09 ± 0.32c	1226.39	<0.001
Germination_vigor (%)	73.0 ± 13.51c	98.0 ± 2.74b	100.0 ± 0.0a	28.0 ± 2.74d	113.65	<0.001
Germination_percentage (%)	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a	52.0 ± 7.58b	200.35	<0.001
Median_germination (day)	2.0 ± 0.0b	2.0 ± 0.0b	1.0 ± 0.0c	2.8 ± 1.09a	9.06	0.001
Mean_germination (day)	2.81 ± 0.24b	2.12 ± 0.04c	1.00 ± 0.00d	3.04 ± 0.44a	66.97	<0.001
Mean Germination Rate (1/day)	0.125 ± 0.000a	0.125 ± 0.000a	0.125 ± 0.000a	0.065 ± 0.009b	198.23	<0.001
Mean Germination Time (day)	2.80 ± 0.23b	2.12 ± 0.04c	1.00 ± 0.00d	3.04 ± 0.44a	67.13	<0.001
Daily Germination Speed (day)	0.403 ± 0.024c	0.482 ± 0.006b	1.00 ± 0.00a	0.265 ± 0.034d	1153.54	<0.001

Values are means ± SD (n=5). Different superscript letters within a row indicate significant differences according to Tukey's HSD test (P<0.001).

Table 2: Physiological germination parameters of chia seeds by harvest year/generation (mean ± SD, n=5)

Parameters	G1	G2	G3	G4	F-value	p-value
Germination_speed (1/day)	5.29 ± 0.89c	7.63 ± 0.20b	8.72 ± 0.31a	1.00 ± 0.00d	321.28	<0.001
Germination_vigor (%)	61.0 ± 15.57b	72.0 ± 5.70b	85.0 ± 3.53a	99.0 ± 2.23a	18.43	<0.001
Germination_percentage (%)	75.0 ± 11.73b	90.0 ± 5.00a	97.0 ± 4.47a	99.0 ± 2.23a	12.61	0.0002
Median_germination (day)	2.6 ± 0.55a	2.0 ± 0.25b	2.0 ± 0.10b	1.0 ± 0.00c	29.33	<0.001
Mean_germination (day)	2.98 ± 0.22a	2.58 ± 0.25b	2.40 ± 0.10b	1.00 ± 0.00c	124.71	<0.001
Mean Germination Rate (1/day)	0.094 ± 0.015c	0.113 ± 0.006b	0.121 ± 0.006a	0.124 ± 0.003a	12.61	0.0002
Mean Germination Time (day)	2.98 ± 0.22a	2.58 ± 0.25b	2.40 ± 0.10b	1.00 ± 0.00c	123.56	<0.001
Daily Germination Speed (day)	0.265 ± 0.045c	0.381 ± 0.010b	0.436 ± 0.016a	0.990 ± 0.022d	735.84	<0.001

Values are means ± SD (n=5). Different superscript letters within a row indicate significant differences according to Tukey's HSD test (P<0.001).

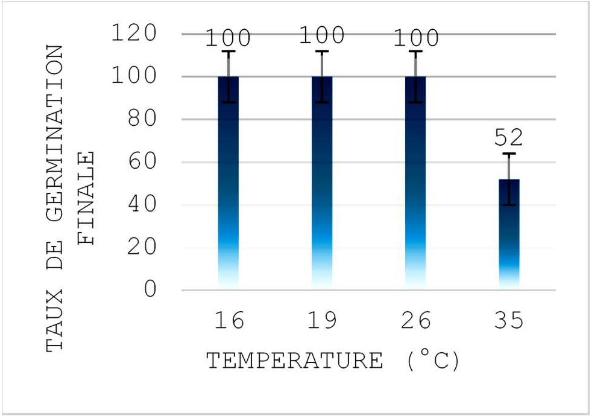

Fig. 2: Effect of temperature on final germination rate of chia.

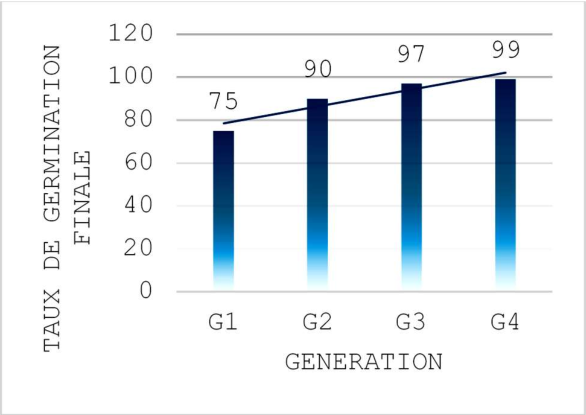

Fig. 3: Effect of generation on final germination rate of chia.

seeds with G1 to G4. Seeds from generation G1 that have been stored since the year 2022 demonstrate a germination rate of 75%. G2 seeds stored since the year 2023 have reached a rate of germination of 90%. Germination rates are reported as 97% for seeds from generation G3 that have been stored since the year 2024. Lastly, G4 seeds that have been stored since the year 2025 have a germination rate of nearly 100% at 99%.

Final germination rate was 100% at 16°C, 19°C and 26°C, while a significant drop to 52% was observed at 35°C. Germination speed and vigor followed the same pattern, being maximal at 26°C (mean germination time = 1.00 ± 0.00 days; DGS = 1.00 ± 0.00day^{-1}) and minimal at 35°C (mean germination time = 3.04 ± 0.44 days; vigor = 28.0 ± 2.74%).

Germination Kinetics (GK)

Germination kinetics chart the cumulative emergence of seedlings over time (24, 48, 72, 96 h, etc.). Rapid, synchronized germination produces a steep kinetic curve, indicating a vigorous seed lot.

To understand the physiological behavior associated with chia seed germination, the number of germinated seeds was monitored daily until DAY 8 of the experiment. Germination curves were generated and displayed in Fig. 4 and 5. Germination curves are sigmoidal in nature and characterized by three phases: latency, exponential growth, and plateau phase, in addition to being modulated by both the temperature and age of the seeds. Latency is absent in the treatment group at 26°C during the investigation with fresh G4 seeds, latency was preserved in older G1 seeds and at the lower temperature of 16°C. The exponential phase increased speed at 19°C and 26°C, however it was inhibited in older G1 seeds and at the critically high temperature of 35°C. Each germination phase is representative of the physiological state of the seeds and their reactions to environmental conditions affecting germination processes. The plateau phase is indicative of the total final germination percentage and ultimately shows the seeds germination capacity. Under optimal conditions of temperature (26°C) with fresh G4 seeds, a synchronous and maximum germination capacity of all viable seeds to 99% on DAY 1 was indicated by the plateau phase of the germination curve. The lack of a latency phase, and faster establishment of the plateau phase indicates that a fully functional germinative metabolism was occurring at this temperature and age of seeds.

The ambient temperature of 19°C resulted in reaching 100% germination plateau at DAY 4, and a relatively low ambient temperature of 16°C reaching plateau phase at DAY 6 while at the same time reaching a progressive slowing of the metabolic process during the germination stage. However, at 35°C the germination curve plateaued at just 44% for DAY 6 causing inhibition of germination mechanism at high temperature. For the older seeds (G1), and ambient temperature, the plateau phase only occurred on DAY 3 but at a 75% level.

Germination Speed (GS)

Germination speed quantifies the rapidity with which seeds transition from dormancy to active growth. Faster speeds are associated with better establishment potential, while delays may signal environmental or aging-related constraints.

Fig. 6 shows that the optimal temperature is 26°C, with a minimal germination time of 1 day, where all seeds germinate almost instantaneously. At 16°C and 19°C, germination speed is moderate (2 to 2.9 days), while at 35°C, germination is slow (7.34 days) and incomplete. The effect of seed age is shown in Fig. 7: the newest seeds (G4) germinate practically right away (1 day), next are G3 seeds (3.2 days), G2 seeds (3.7 days), and the slowest germination time was G1 (4.5 days).

Mean Germination Time (MTG)

Mean germination time (MTG) is defined as the average time to reach final germination. A shorter MTG is advantageous and is correlated with efficient physiological processes and seed vigor (Fig. 8 and 9).

Mean Germination Rate (MGR)

The Mean Germination Rate (MGR) indicates the average number of seeds germinating over the days. As an integrative parameter of germinative dynamics across experimental conditions, it will be used in the analysis of germinative GD using compositional data analysis (Fig. 10 and 11).

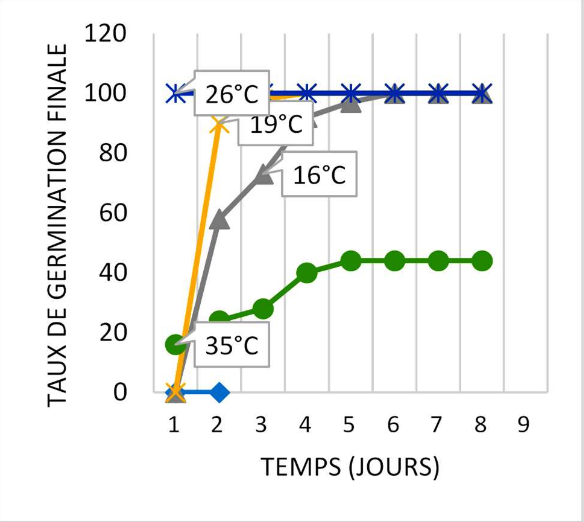

Fig. 4: Effect of temperature on kinetics germination of chia.

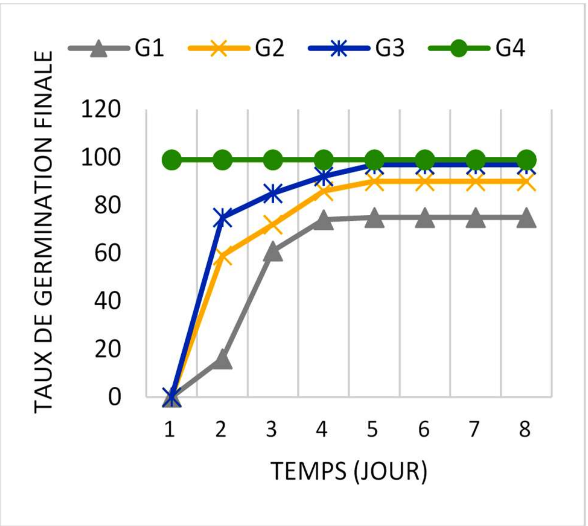

Fig. 5: Effect of generation on kinetics germination of chia.

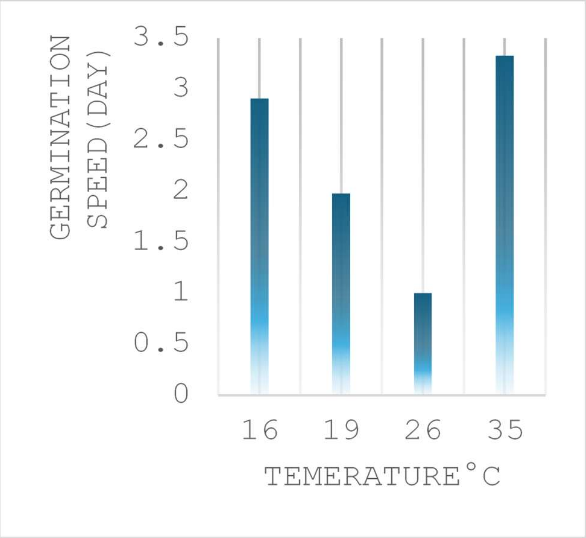

Fig. 6: Effect of temperature on germination speed of chia.

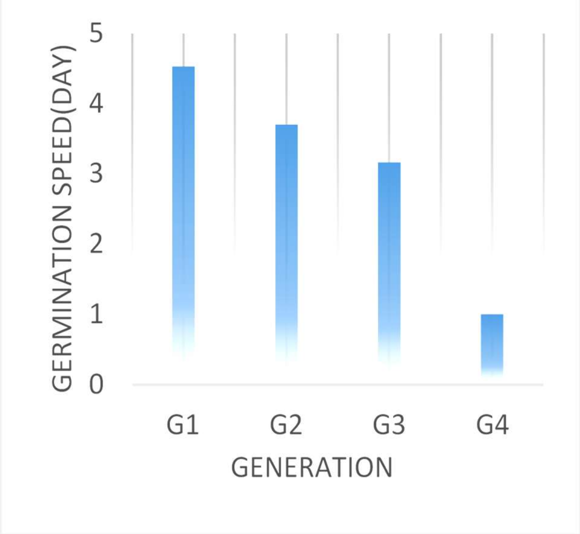

Fig. 7: Effect of generation on germination speed of chia.

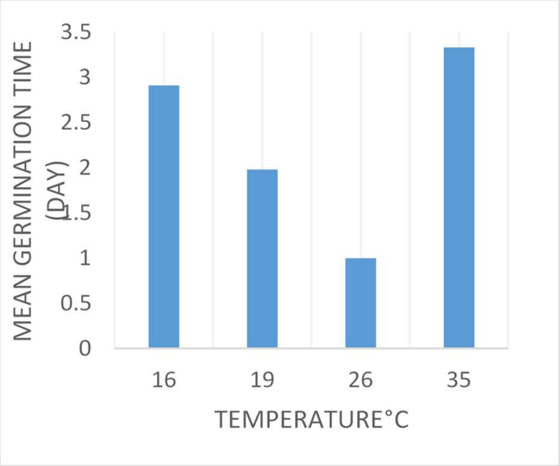

Fig. 8: Effect of temperature on mean germination time of chia.

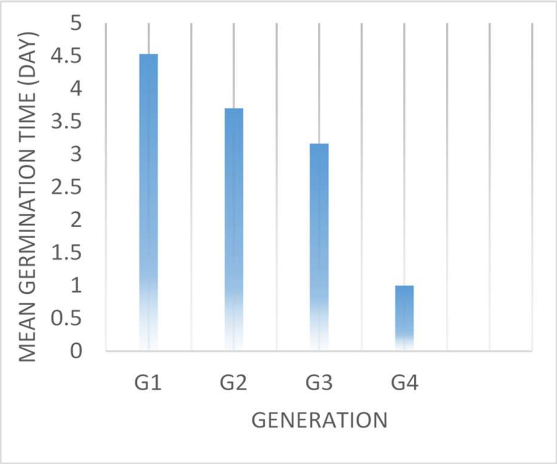

Fig. 9: Effect of generation on mean germination time of chia.

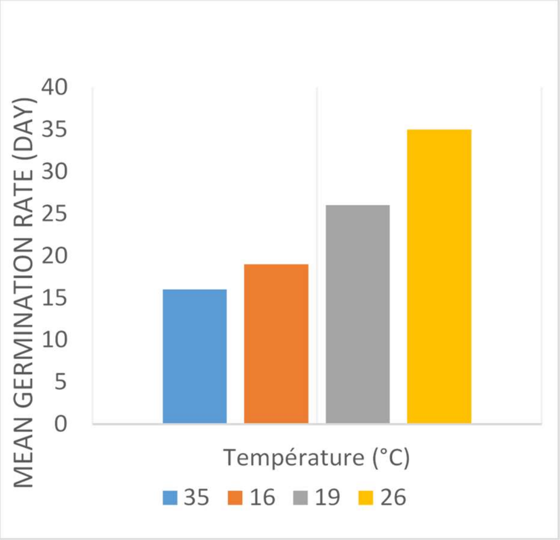

Fig. 10: Effect of temperature on mean germination rate of chia.

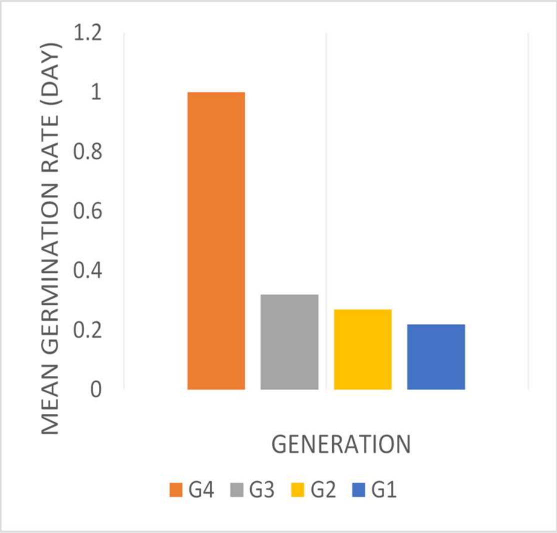

Fig. 11: Effect of generation on mean germination rate of chia.

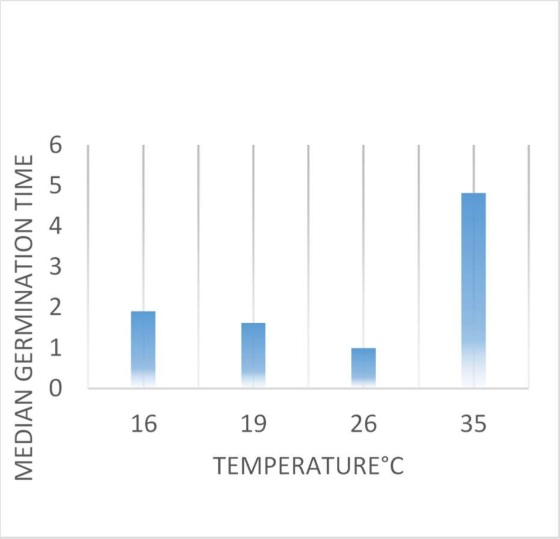

Fig. 12: Effect of temperature on median germination time of chia.

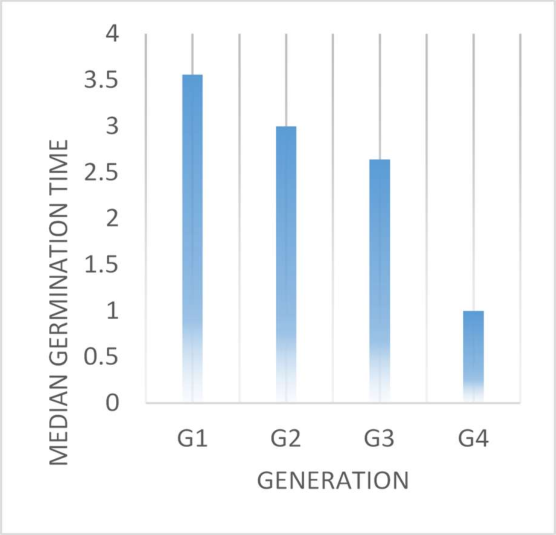

Fig. 13: Effect of generation on median germination time of chia.

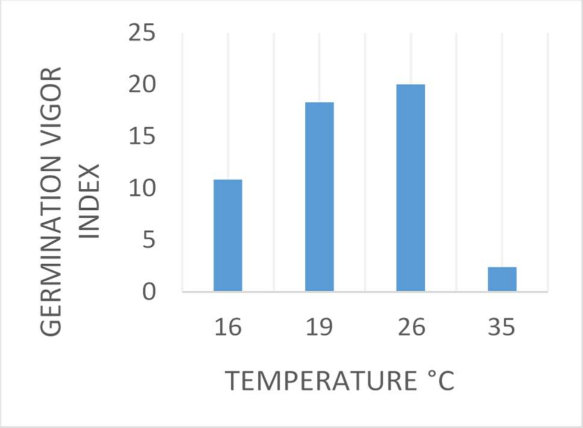

Fig. 14: Effect of temperature on germination vigor index of chia.

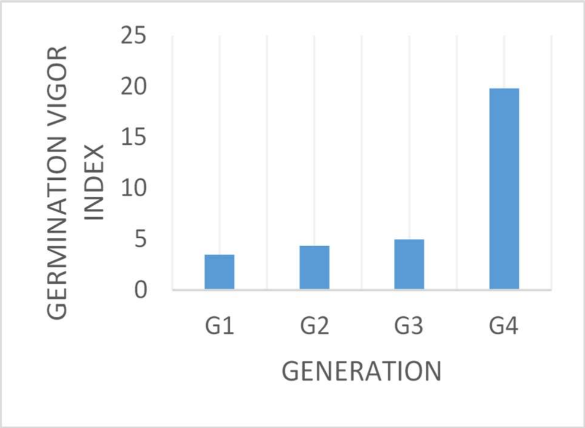

Fig. 15: Effect of generation on germination vigor index of chia.

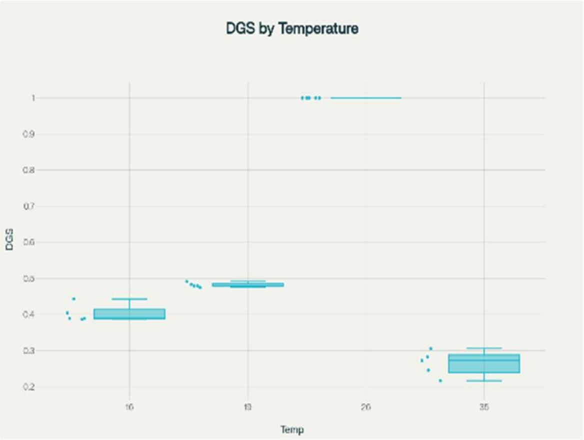

Fig. 16: Effect of temperature on Daily Germination Speed of chia.

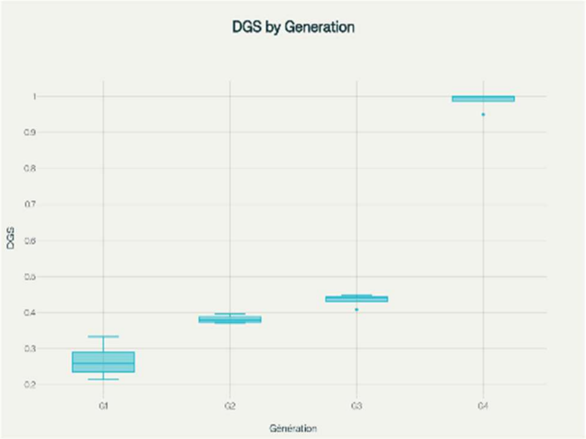

Fig. 17: Effect of generation on Daily Germination Speed of chia.

Median Germination Time (T50)

The median germination time (T50) indicates the time that half the seeds will germinate. In our analysis, a lower T50 is indicative of fast, uniform germination, while a higher value indicates slower or heterogeneous emergence within the seed lot.

At 26°C, T50 is 1 day, demonstrating eventual near instantaneous germination. With thermal stress at 35°C, T50 increased to 4.82 days is also indicative of inhibition. Newer seeds (G4) had a T50 that was significantly less than older generations G1 to G3 ($P<0.001$), indicating temperature and seed age both impacted germination inhibition (Fig. 12 and 13).

Germination Vigor Index (GVI)

The Germination Vigor Index (GVI) considers the speed and completeness of germination. High GVI values indicate seed lot quality by measuring a rapid and synchronous seedling emergence (Fig. 14 and 15).

Daily Germination Speed (DGS)

Daily Germination Speed (DGS) is a daily measure of speed seeds germinated during the test. Higher DGS indicated strand seed lot performance and adaptation to conditions (Fig. 16 and 17).

DISCUSSION

This study provides new insights into the physiological parameters governing chia (*Salvia hispanica L.*) seed germination under Mediterranean conditions, highlighting the close interaction between temperature regimes and seed aging. Recent studies on oilseed crops and pseudocereals, have confirmed thermal stress as one of the most significant abiotic factors contributing to reduced seed germination and seedling vigor (Del Buono et al., 2021; Mittler et al., 2025). Projections of global climate systems indicate that an increasing frequency of heat events where soil temperatures exceed 30°C will significantly hinder crop establishment. The current work provides strong evidence and extends previous studies of germination of chia seed in Mediterranean climate conditions. The best germination occurred at moderate temperatures of 16°C to 26°C, consistent with studies done globally which show that a moderate thermal range is needed to achieve maximum viability and vigor (Stefanello et al., 2022; Sampayo-Maldonado et al., 2025). Based on our assessment, temperatures above 30°C resulted in reduced speed of germination and reduced final rate of emergence, indicating disruption of normal germination activity seen in olives and other oilseed crops (Carvalho & Nakagawa, 2012; Oliveira et al., 2014). The temperature of 35°C made germination incomplete and very slow, indicating severe limitations imposed by thermal stress.

Increased temperature affects many metabolic processes, with the major accumulated products of metabolism being overactive oxidants (ROS) that lead to oxidative damage, unstable or ruptured plasma membranes, and the absence (loss) of the action of certain enzymes (Mittler et al., 2025). When exposed to heat, chia plants activate specific signal(s) to induce adaptive responses to stress (such as antioxidants), but over-the-top stress results from a continued overabundance of ROS that ultimately deplete or overwhelm the ability of the seeds or seedlings to maintain their integrity; such lipid degradation occurs due to lipid peroxidation or protein denaturation associated with high temperatures, as evidenced by reduced Vigor Indices and increased mean germination time of chia. (Riedesel et al., 2024). Germination kinetics data indicated that germination occurred in a normal classic sigmoidal curve, with a rapid attainment of plateau germination occurring at 26°C, as well as in seeds from the most recent harvest (G4 in 2025). The latency phase increased with seeds that were older, as well as with reduced temperatures, which reflects the reduced activity and homogeneity of the metabolic processes. These patterns observed were similar to the theoretical progression patterns of seed germination under stress for various Mediterranean crops (Haghighi et al., 2021; Rodríguez et al., 2024).

Our research confirms that seed aging has a substantial role in lowering viability and synchrony. Generational assessment indicates gradual declining trends in all physiological parameters with storage time. The most apparent was that G4 seeds germinated almost instantly (mean time = 1.00 ± 0.00 days, vigor = 99.0 ± 2.23%), while G1 seeds exhibited slow and less synchronous germination (mean = 2.98 ± 0.22 days, vigor = 61.0 ± 15.57%). In the studies of Yehia et al. (2024) and Xing et al. (2025), as well as these researchers' work, we see that there is a direct correlation between the amount of oxidative stress applied to a seed while in storage (at room temperature) and the decline of viability in vigorously sprouting seeds. The rates of viable sprouting decrease as a seed ages, due to both an increase in the oxidative stress applied during storage and the loss (through leakage) of cellular solutes, as well as the degradation of enzymes responsible for catalase and superoxide dismutase activities. This analysis of chia seeds has shown that proteins essential for their germination, and that were vital for their energy production and restoration, have degraded significantly as these seeds have aged significantly (Riedesel et al., 2024). These observations support a link between molecular factors such as heat-shock proteins and storage sugars that may facilitate seed longevity (Haghighi et al., 2021; Rodríguez et al., 2024).

Other oilseed and pseudo-cereal crops also exhibit similar mechanisms. For example, quinoa can have a 90%-drop in germination rates after 3 years and experience slower and more variable germination/emergent rates (Benidire et al., 2015). Additionally, amaranth is similarly highly sensitive to prolonged exposure to heat; therefore, both quinoa and amaranth will have lower establishment rates, as well as lower established vigour indexes after extended periods of storage (Muñoz et al., 2013; Din et al., 2021) due to their increased susceptibility to metabolic changes resulting from prolonged storage.

The metabolic profiles of the sunflower and rapeseed crops show that the reduction in germination vigour can result from imbalances between energy supplies, disruption of the fatty acid metabolic pathway and hormonal hypotension or imbalance (see Gibberellins and Abscisic Acid). (Del Buono et al., 2021). A notable aspect of seed aging is its genetic dimension: genotypic variation in resistance to storage conditions has been reported in chia, quinoa and soybean (Arif et al., 2022). Selecting genotypes with high membrane stability, elevated basal antioxidant levels and enhanced repair capacity could provide promising pathways to mitigate the combined negative effects of heat and aging. Seed priming and the use of controlled storage treatments have proven to be beneficial for restoring viability in aged seeds through rejuvenation of the aged seeds after exposure to thermal stress, although the ability of these techniques to rejuvenate aged seeds is dependent on initial quality of the seed and environmental conditions around the seed during storage (Xing et al., 2025).

Our multi-parameter approach, in particular these new measures of DGS, MGR and MTG, reflects even greater sensitivity for differentiating lots and treatments, which can support more informed decisions in an agri-industrial context. Based on the data collected from this study in Morocco, it is promising because the benchmarks reached are similar, and in some cases superior, to those published in the international literature for chia and other oil-producing species that face similar climate-induced environmental limitations. Field observations from the Gharb plain, Morocco agree with worldwide observations of an increase in the incidence of climate instability (fluctuating climate) along with the increasing summer heat. Because of increased climate changes (fluctuating), we now face many new challenges in crop establishment. The results show that, as time goes by, we will continue to see the decline in germination percentages between the first year and the fourth year, as well as the increase in the length of time required to germinate seeds and lower amounts of vigor, will result in a greater need for strict monitoring of seed quality and selecting the right date for planting. (FAO, 2022; IPCC, 2022). Importantly, the effects of heat and aging are not simply additive but often synergistic: seeds already weakened by age respond particularly poorly to supraoptimal temperatures, with low emergence and high mortality. The synergy between this approaches indicates that integrated strategies consisting of genetic selection, improved post-harvest storage, and biostimulants or seed treatments will help increase physiological resilience in chia. Although physiological constraints in chia compared to oilseed and pseudocereal crops appear to be mostly the same, their intensity and resultant agronomic implications will differ based on the genotype, climate, and management practices.

In summary, the evidence supports three main recommendations for sustainable chia cultivation: plan sowing time during moderate temperatures (preferably 19–26°C) to favor establishment and yield; rotate seed lots and handle storage carefully to maintain physiological freshness and uniformity; and give attention to appropriate physiological testing in order to produce lots with better vigor. Identifying metabolic and genetic characteristics that can be selectively bred for chia may benefit from research on other crops with increased heat tolerance, notably quinoa. In addition, innovations in the application of new seed treatments as well as an increase in the number of options available to ensure proper quality control of seeds can result in extending the viability period of the seed lots and facilitating crop production under more challenging conditions. By considering both thermal and temporal stresses, this study provides a reproducible methodology for improving chia seed germination rates to increase resilience and yield in Mediterranean agro-ecosystems, and underscores the importance of combining genetics, seed physiology and agronomic management to support food security in vulnerable regions such as Morocco.

Conclusion

This article presents strong evidence suggesting that temperature and seed age are key factors affecting the physiological germination success and vigor of chia (*Salvia hispanica L.)* seeds from the Gharb region of Morocco. Overall, optimal results were consistently observed for all germination parameters at sowing temperatures between 19°C and 26°C, where seeds germinated relatively quickly, uniformly, and at high percentage germination. Meanwhile, extreme conditions e.g., 35°C and extended seed storage significantly reduced seed viability, vigor, and synchrony among all physiological metrics. In regards to seed lots, all tested parameters (G4–2025) germinated better than all older lots and suggest the need to renew seed stock and ensure adequately controlled storage. The use of a multi-parametric approach (DGS, MGR, MTG) allowed for a sensitive differentiation of lot performance. This offers a sound application of a methodology for agricultural decision-making and improving chia supply chains and farming systems in Mediterranean conditions. Overall, these findings support local producers need to sow at moderate temperatures and using recently harvested seeds in order to maximize chia productivity and improve resilience. The protocols presented here provide an excellent baseline for future studies to investigate the molecular and physiological processes of how chia seeds age and the stress responses of chia seeds to climate stress. Furthering this research might assist in developing best practices for storage, distribution, and sustainable intensification of chia and similar crops in semi-arid and Mediterranean regions.

In summary, addressing temperature and seed freshness are fundamental levers to enhance chia germination, field establishment, and agro-industrial value, while responding to climate variability and advancing seed physiology science for future emerging staple crops. The research supports the use of climate-smart agriculture by calling for the alignment of planting dates, the storage of seeds and the selection of seed varieties with the predicted increase in temperature in the semi-arid part of the Mediterranean.

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Data Availability: All the data is available in the article.

Ethics Statement: This study was conducted on plant seeds only and did not involve humans or animals. Therefore, formal approval from an institutional ethics committee was not required, and all experimental procedures complied with relevant institutional and national guidelines.

Author's Contribution: Aicha Rossafi: Conducted research, data collection and write-up, interpretation of data. Sanaa El aidouni: Conceptualization, designing, supervision. Mohamed Rossafi: Analysis of data and arrangement of tabulated data and statistical analysis**.** Mohammed Ouhssine: Helped in format setting and citations, validation of the manuscript

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