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Seed Quality and Germination Dynamics in Small-Grain Cereals

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ABSTRACT

Objective: To determine the quality and germination dynamics of seeds of rye cv. Elbon, wheat cv. Valles, and triticale cv. T5.

Design/methodology/approach: Seeds were separated by size (small and large) and subjected to different conditioning treatments (accelerated aging). Study variables included the number of pure seeds, inert material, other seeds, thousand-seed weight, bulk density, moisture content, germination percentage, emergence speed, mean germination time, germination rate, germination speed coefficient, and germination uncertainty and synchrony indices. Analysis of variance was conducted using a randomized factorial design with four replications for each species and seed size. Means were compared using Tukey's test ($P<0.05$).

Results: The rye lot exhibited a long shelf life and medUIm vigor, while wheat and triticale seeds were short-lived and of low vigor. In all three species, large seeds were more vigorous than small seeds; however, seed size did not affect the temporal distribution of germination. Aging reduced germination percentage, emergence speed, germination rate, and synchrony index, while increasing mean germination time and the uncertainty index.

Limitations on study/implications: None

Findings/conclusions: Large seeds of rye, wheat, and triticale exhibit higher vigor, while seed aging negatively affects germination dynamics.

Keywords: accelerated aging, germination, seed size, *Secale cereale* L., *Trititcum aestivum* L., X *Triticosecale* Wittmack

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INTRODUCTION

The use of high-quality germplasm is crucial during the initial stage of any crop, as it enables successful seedling establishment (Steiner *et al.*, 2019). Seed quality encompasses physical, physiological, genetic, and sanitary attributes (Bewley *et al.*, 2013; Carranza-

González *et al.*, 2022). These attributes must be in balance for a grain lot to be classified as high quality (Costa *et al.*, 2021). Among the parameters that determine seed quality, physical quality is particularly relevant and includes aspects such as purity and grain size. Genetic quality ensures that the seed maintains a high degree of similarity to the original germplasm. Likewise, sanitary quality focuses on ensuring that the grain is free of pests and diseases. Finally, physiological quality refers to the germinative capacity and vigor of the germplasm under field conditions at the time of sowing (Delouche, 1985).

Crop yield and efficient resource use depend on the successful establishment of seedlings; seed vigor determines germination capacity and the rapid, uniform establishment of seedlings under diverse agroclimatic conditions (Finch-Savage & Bassel, 2016). Seeds reach their maximum vigor when the mother plant attains physiological maturity (Delouche, 1985; Costa *et al.*, 2021). However, grain is harvested only once its moisture content falls below 14% (harvest maturity) to prevent mechanical damage during harvest and storage (Copeland & McDonald, 2001). Between physiological and harvest maturity, seeds remain on the mother plant and are exposed to adverse environmental conditions that may reduce their quality (Copeland & McDonald, 2001; Costa *et al.*, 2021). Moreover, seeds are rarely sown immediately after harvest; consequently, they may be exposed to suboptimal conditions during storage (Copeland & McDonald, 2001; Domínguez-Martínez *et al.*, 2024a).

Germination is a developmental response of an individual seed that occurs at a specific moment; however, within a lot or treatment, seeds may germinate at different times (Orchard, 1977; Kader, 2005). For example, two seed lots may exhibit the same germination percentage, yet one may complete germination four days earlier than the other. This demonstrates that germination percentage alone is insufficient for comparing seed lots. To address this issue, various methods and techniques have been proposed. Time, rate, uniformity, and synchrony are parameters that can be measured to describe the dynamics of the germination process (Kader, 2005; Ranal & Santana, 2006).

Physical quality, physiological quality, and germination dynamics may be affected in seed lots after a storage period. Based on this, the objective of this study was to determine the quality and germination dynamics of rye cv. Elbon, wheat cv. Valles, and triticale cv. T5 seeds.

MATERIALS AND METHODS

This study was conducted at the Colegio de Postgraduados, Montecillo Campus. The site is located at an altitude of 2,250 m and has a temperate subhumid climate with summer rainfall, classified by García (1998) as Cb(wo)(w)(i')g. The mean annual temperature is 15 °C, and the average annual precipitation is 645 mm (García, 1998).

Three seed lots classified as "Declared" category were sampled. The first lot corresponded to rye cv. Elbon, the second to wheat cv. Valles, and the third to triticale cv. T5. For each lot, four primary samples were obtained and mixed to form a 1-kg composite sample. The composite sample was homogenized in the laboratory, and from it a 500-g working sample was extracted to determine the physical and physiological quality and the vigor of the seeds.

Moisture content was determined using the direct method from a 300-g sample collected separately for each species. In the laboratory, two 10-g subsamples (per species) were taken and placed in aluminum containers with lids and known weights. The containers with the seed samples were placed in a drying oven at 130 °C for two hours. Moisture content was calculated using the following formula:

$$\%\,moisture = \left(\frac{P_2 - P_3}{P_2 - P_1}\right)\times 100$$

where: P_1 corresponds to the weight of the container and its lid (g), P_2 is the weight of the container, lid, and seed (g), and P_3 is the weight of the container, lid, and seed after oven drying. For the determination to be accepted as valid, the difference in moisture percentage between the two subsamples of each species had to be less than 0.2%.

Physical quality was determined based on the amount of pure seed (PS), inert matter (IM), other seeds (OS), thousand-seed weight (TSW), bulk density (BD), and moisture content (MC), following the methodologies proposed by AOSA (2014). Physiological quality was evaluated through germination percentage (GP), emergence speed (ES; Maguire, 1962), and the accelerated aging test (Delouche & Baskin, 1973), using the modifications proposed by Huber *et al.* (1982) and Kim *et al.* (1985).

Mean germination time (MGT), mean germination rate (MGR), germination speed coefficient (GSC), germination uncertainty index (UI), and germination synchrony index (SI) were calculated to describe the germination dynamics of the different seed lots (Ranal & Santana, 2006).

Seeds were separated by size using a 2.38-mm sieve. All seeds retained on the sieve were classified as large (L), while those that passed through the mesh were considered small (S). Conditioning treatments were applied to 800 seeds of each size: 400 seeds underwent accelerated aging (AA), and the remaining 400 were left without aging (NA). The combination of the two factors (size × conditioning) resulted in four treatments, with four replications of 100 seeds per species.

The germination test for each species was conducted in a 2.5 m^2 seedbed using sterilized sand as the substrate. The distribution of treatments and replications was randomized within each seedbed. Each replication was sown in four rows, with 25 seeds per row, placed at a depth of 2 cm and spaced 3 cm apart within and between rows.

Analysis of variance for physiological quality variables was performed using a randomized factorial experimental design, with four replications for each species and seed size. Means were compared using Tukey's test ($P<0.05$). Data analysis was conducted using SAS software v. 9.4 (SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Seeds classified as "Declared" or "Commercial" must comply with the standards established for the "Certified" category (SNICS, 2014). In the present study, only the wheat seed lot met the minimum requirement of 98% pure seed, whereas rye and triticale did not comply with this standard (Table 1). All three lots exceeded the maximum allowed limit (1%) for inert matter. The regulation allows 0.02% for other seeds; in this regard, the rye and triticale lots did not meet this requirement.

The TSW of rye was 8 to 15 g lower than that of wheat and triticale. Rye also had a lower bulk density compared to the other two species. Authors such as Voloshchuk *et al.* (2023) compared the TSW of three varieties of each species and reported that rye consistently exhibits a lower TSW than wheat and triticale. Furthermore, Aprodu and Banu (2016) found that rye grains are smaller and less compact, which explains why its TSW and BD are lower than the values observed in wheat and triticale. Although rye grains were smaller compared to wheat and triticale, the values obtained in the present study fall within the range reported for the species. Hansen *et al.* (2004) found that among 19 rye genotypes, TSW ranged from 20 to 39 g, while BD ranged from 70.2 to 80.6 kg hL^{-1}. In another study, Carranza-González *et al.* (2022) evaluated 24 wheat genotypes and reported that TSW varied between 29 and 48 g and BD ranged from 76 to 82 kg hL^{-1}. The values obtained for wheat cv. Valles in the present study fall within the aforementioned ranges. The interaction of genetic, epigenetic, and environmental factors influences grain development, which ultimately determines seed yield and quality (Wang & Sun, 2021). In general, large seeds are preferred because they have better-developed embryos, a greater amount of reserves to support early growth (Carvalho & Nakagawa, 2000), and better field performance; however, results regarding germination, emergence, and growth vary among species (Zareian *et al.*, 2013). Additionally, evidence indicates that selecting cultivars with higher TSW can increase grain yield (Paquini *et al.*, 2016).

Seeds from all three lots had moisture contents below the upper limit of 13% established for the Declared category (SNICS, 2014). Moisture content plays a key role in seed deterioration or preservation during storage (Pomeranz, 1992; Ranganathan & Groot, 2023). Harrington (1972) proposed, as a general rule, that for grains with 5 to 14% moisture, shelf life doubles each time moisture content decreases by 1%.

In the rye lot, large (L) seeds germinated 8% more and emerged at a higher rate (2.6 plants day^{-1}) than small (S) seeds (Table 2). Likewise, mean germination time was higher in the small seeds (0.3 days) compared to the large seeds. The mean germination rate of large seeds was 0.01 plants day^{-1} higher than that of small seeds. Seed size had no significant effect ($P<0.05$) on the germination speed coefficient or on the germination uncertainty and synchrony indices. On the other hand, the aging treatment reduced germination and emergence rate by approximately 11% (5.5 plants day^{-1}) in the small seeds. Additionally, mean germination time was 0.9 days longer in seeds subjected to accelerated aging.

Table 1. Physical quality of rye cv. Elbon, wheat cv. Valles, and triticale cv. T5 seeds.

	PS[1] (%)	**IM (%)**	**OS (%)**	**TSW (g)**	**BD (kg hL^{-1})**	**MC (%)**
Rye cv. Elbon	97.11	2.05	0.84	21.38	76.34	6.50
Wheat cv. Valles	98.80	1.20	0.00	30.25	77.22	8.00
Triticale cv. T5	97.23	2.55	0.22	36.63	77.22	8.50

[1] PS=pure seed, IM=inert matter, OS=other seeds, TSW=thousand-seed weight, BD=bulk density, and MC=moisture content.

Table 2. Germination percentage (GP), emergence speed (ES), mean germination time (MGT), mean germination rate (MGR), germination speed coefficient (GSC), and germination uncertainty (UI) and synchrony (SI) indices of rye cv. Elbon seeds classified by size and subjected to different conditioning treatments.

Source of variation		**GP (%)**	**VE (plants d^{-1})**	**MGT (d)**	**MGR (plants d^{-1})**	**GSC**	**UI**	**SI**
Size	S[1]	82.0^{b}	17.7^{b}	4.8^{a}	0.21^{b}	29.2	1.3	0.5
	L	90.0^{a}	20.3^{a}	4.5^{b}	0.22^{a}	28.8	1.0	0.5
Conditioning	AA	80.2^{b}	16.2^{b}	5.1^{a}	0.20^{b}	29.9	1.6^{a}	0.4^{b}
	NA	91.7^{a}	21.7^{a}	4.2^{b}	0.23^{a}	28.1	0.8^{b}	0.6^{a}
Interaction	S × AA	74.7	14.2	5.4^{a}	0.18	29.2	1.7	0.4
	S × NA	89.2	21.1	4.3^{c}	0.23	29.1	0.9	0.6
	L × AA	85.7	18.2	4.8^{b}	0.21	30.5	1.4	0.4
	L × NA	94.2	22.4	4.2^{c}	0.24	27.0	0.6	0.7

[1] S=small seed, L=large seed, AA=seeds subjected to accelerated aging, and NA=non-aged seeds. Values presented for seed size and conditioning correspond to the mean of eight observations. Means for the interaction of factors are based on four observations. ^{a,b} Different letters within a column and source of variation indicate statistically significant differences, while the absence of letters indicates no significant difference (Tukey; $P \leq 0.05$).

The interaction of both factors had the greatest effect on the small aged seeds (S × AA), increasing mean germination time by 0.6 days compared to large aged seeds. The mean germination rate was higher in the non-aged treatment (0.03 plants day^{-1}) compared to the aged treatment. Finally, the germination uncertainty index in aged seeds was twice that of the non-aged seeds, whereas synchrony was higher (0.2) in the latter group.

Germination of small seeds in the wheat lot was 23.7% lower than that of large seeds. Among the conditioning treatments, the difference (42.9%) favored the non-aged seeds (Table 3). L and NA seeds emerged 4.5 and 9.6 plants day^{-1} faster than S and AA seeds, respectively. The size × conditioning interaction was significant for ES, and it was observed that aging negatively affected this variable regardless of seed size; however, the most pronounced reduction occurred in small aged seeds. Significant differences ($P<0.001$) for mean germination time were found only between conditioning treatments, with aged seeds taking 1.7 days longer to germinate.

For mean germination rate, significant differences were observed between conditioning treatments ($P<0.001$) and for the interaction ($P=0.028$). Non-aged seeds germinated at a rate 0.05 plants day^{-1} higher than aged seeds. Additionally, the negative effect of the AA treatment was of similar magnitude in both seed size categories, and large non-aged seeds (L × NA) had a higher germination rate (0.05 plants day^{-1}) compared to small non-aged seeds (S × NA). Greater germination uncertainty (UI) was found in aged seeds (AA), while synchrony (SI) was higher in non-aged seeds (NA) ($P<0.001$).

Seed size, conditioning, and the interaction of factors were significant ($P<0.001$) for GP, ES, MGT, and MGR (Table 4). Small seeds (S) germinated less (9.5%) and at a lower rate (2.7 plants day^{-1}) than L seeds. The aging treatment (AA) reduced GP and ES by 21% (6.3 plants day^{-1}). Small seeds in combination with accelerated aging (S × AA) showed the most severe reduction in germination percentage and emergence speed. MGT increased

Table 3. Germination percentage (GP), emergence speed (ES), mean germination time (MGT), mean germination rate (MGR), germination speed coefficient (GSC), and germination uncertainty (UI) and synchrony (SI) indices of wheat cv. Valles seeds classified by size and subjected to different conditioning treatments.

Source of variation		PG (%)	VE (plants d^{-1})	MGT (d)	MGR (plants d^{-1})	GSC	UI	SI
Size	S[1]	36.3^{b}	6.6^{b}	6.1	0.16	31.4	1.7	0.3
	L	60.0^{a}	11.1^{a}	6.0	0.17	28.1	1.7	0.4
Conditioning	AA	26.7^{b}	4.0^{b}	6.9^{a}	0.14^{b}	30.7	2.1^{a}	0.2^{b}
	NA	69.6^{a}	13.6^{a}	5.2^{b}	0.19^{a}	28.8	1.3^{b}	0.5^{a}
Interaction	S × AA	14.5	2.2^{d}	6.8	0.14^{c}	32.0	1.9	0.2
	S × NA	58.2	11.0^{b}	5.5	0.18^{b}	30.8	1.5	0.4
	L × AA	39.0	5.8^{c}	7.0	0.14^{c}	29.4	2.2	0.2
	L × NA	81.0	16.3^{a}	5.0	0.19^{a}	26.9	1.2	0.5

[1] S=small seed, L=large seed, AA=seeds subjected to accelerated aging, and NA=non-aged seeds. Values presented for seed size and conditioning correspond to the mean of eight observations. Means for the interaction of factors are based on four observations. [a,b] Different letters within a column and source of variation indicate statistically significant differences, while the absence of letters indicates no significant difference (Tukey; P≤0.05).

Table 4. Germination percentage (GP), emergence speed (ES), mean germination time (MGT), mean germination rate (MGR), germination speed coefficient (GSC), and germination uncertainty (UI) and synchrony (SI) indices of triticale cv. T5 seeds classified by size and subjected to different conditioning treatments.

Source of variation		PG (%)	VE (plants d^{-1})	MGT (d)	MGR (plants d^{-1})	GSC	UI	SI
Size	S[1]	59.9^{b}	11.8^{b}	5.6^{a}	0.18^{b}	29.1^{b}	1.8	0.3
	L	69.4^{a}	14.5^{a}	5.1^{b}	0.20^{a}	33.1^{a}	1.7	0.4
Conditioning	AA	54.1^{b}	10.0^{b}	5.9^{a}	0.17^{b}	31.0	1.9^{a}	0.3^{b}
	NA	75.1^{a}	16.3^{a}	4.8^{b}	0.21^{a}	31.2	1.5^{b}	0.4^{a}
Interaction	S × AA	44.3^{c}	7.3^{c}	6.4^{a}	0.16^{c}	28.0	2.0	0.3
	S × NA	75.5^{a}	16.3^{a}	4.8^{c}	0.21^{a}	30.1	1.6	0.4
	L × AA	64.0^{b}	12.7^{b}	5.3^{b}	0.19^{b}	34.0	1.9	0.4
	L × NA	74.8^{a}	16.2^{a}	4.8^{c}	0.21^{a}	32.3	1.5	0.4

[1] S=small seed, L=large seed, AA=seeds subjected to accelerated aging, and NA=non-aged seeds. Values presented for seed size and conditioning correspond to the mean of eight observations. Means for the interaction of factors are based on four observations. [a,b] Different letters within a column and source of variation indicate statistically significant differences, while the absence of letters indicates no significant difference (Tukey; P≤0.05).

by 0.5 days in small seeds, 1.1 days with EA, and the interaction of factors was significant ($P<0.001$). Regarding MGR, the opposite behavior to MGT was observed for both factors and their interaction. Large seeds showed a germination speed coefficient 4% higher than the S seeds.

For the germination uncertainty and synchrony indices, differences were only found between conditioning treatments ($P<0.001$ and 0.004, respectively). Uncertainty increased by 0.4 when seeds were subjected to AA. Conversely, synchrony was higher (0.1) in seeds that were not conditioned.

In México, as previously established, commercial seeds must comply with the regulations corresponding to the Certified category. Regarding germination, the cereal seed grading rule sets 90% as the minimum (SNICS, 2014). In this case, only in the rye lot were large (L), non-aged (NA), and L × NA seeds found to meet or exceed this requirement. On the other hand, the accelerated aging treatment (AA) negatively affected germination in all three species; however, the most considerable damage was observed in wheat cv. Valles. In this regard, Delouche and Baskin (1973) mention that a seed lot maintaining more than 80% germination after accelerated aging (AA) is considered long-lived, whereas lots failing this criterion are considered short-lived.

Mathias and Coelho (2021) classified soybean seed lots as high vigor when they retained ≥85%, medUIm vigor 70-84%, and low vigor <70% of their germination after artificial aging treatment. In general terms, the rye lot in the present study can be considered long-lived with medUIm vigor. In contrast, wheat and triticale seeds were short-lived and of low vigor. However, these findings contradict previous evidence indicating that rye has lower longevity compared to other small-grain cereals (Peters *et al.*, 1964; Specht *et al.*, 1997).

Emergence speed is a methodology that allows comparison of vigor among samples from the same seed lot (Maguire, 1962). In this regard, high values indicate that those samples are more vigorous than the others (Ranal & Santana, 2006). In contrast to the results of the present study, in a barley cv. Brennus lot, small seeds emerged at a higher speed than large seeds; moreover, the negative effect of aging was more pronounced on small seeds (Domínguez-Martínez *et al.*, 2024b). In another study, seed size and its interaction with the aging treatment did not have a significant effect on VE in oat seeds cv. Turquesa (Domínguez-Martínez *et al.*, 2024a).

Germination is a response of seed development that occurs over time; however, within a lot or treatment, individual seeds may respond (germinate) at different times (Talská *et al.*, 2020). Consequently, germination percentage alone is insufficient for comparative analysis between datasets. Therefore, various methods and techniques have been proposed to measure germination and address this issue. Time, rate, uniformity, and synchrony are aspects that can be measured to describe the dynamics of the germination process (Kader, 2005; Ranal & Santana, 2006). Mean germination time (MGT) indicates the day on which the mean germination occurs; consequently, a low MGT value reveals that that seed population reaches germination more quickly compared to others (Orchard, 1977). Mean germination rate (MGR) is calculated as the reciprocal of MGT (1/MGT); thus, high values indicate a higher daily germination rate in that population (Ranal & Santana, 2006). The germination speed coefficient (GSC) shows the rate at which germination occurs (Jones & Sanders, 1987). This value increases as the number of germinated seeds rises and the time required for germination decreases (Talská *et al.*, 2020). On the other hand, UI is an adaptation of the Shannon index that measures the degree of uncertainty associated with the distribution of relative germination frequency; in other words, it measures the dispersion of germination over time (Ranal & Santana, 2006). Conversely, SI describes the level of overlap in germination, that is, how concentrated this process is over time (Ranal &

Santana, 2006). Seed lots are preferably characterized by low UI values and high SI values to promote rapid establishment and uniformity of crops.

CONCLUSIONS

The rye lot evaluated in the present study was long-lived with medium vigor. Wheat and triticale seeds were short-lived and of low vigor. In all three species, large seeds were more vigorous than small seeds. Large seeds of the three species germinated more and at a higher speed compared to small seeds; however, seed size had no effect on the distribution of germination over time. Aging significantly reduced germination, emergence speed, mean germination rate, and synchrony index, while increasing mean germination time and germination uncertainty.

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