

Article

The Effect of Different Crop Production Systems on Seed Germination and Longevity in Winter Wheat (*Triticum aestivum* L.)

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Abstract

Seed germination performance and storability are fundamental components of seed quality and critical for successful crop establishment. However, information on the impact of different crop production systems on the quality and storability of seed material is still limited. Therefore, the aim of this study was to compare the effects of different crop production systems (ecological, integrated, conventional, and monoculture) on seed germination and predisposition for storage. The research was carried out on four varieties of winter wheat. Seed material was produced within a two-year period, during which different weather conditions occurred. Four germination-related traits were assessed: germination capacity NS (%), total germination (TG%), time to reach 50% germination (t50) and the area under the germination curve (AUC). The results demonstrated that the cultivar, the cultivation system and the year of study had a significant impact on germination characteristics. The ecological system ensured the highest germination rate in fresh seeds. However, in the CD test, the conventional system demonstrated the highest levels of stress resistance and stability, suggesting the best storage potential. The significant system × variety interaction demonstrates the importance of accurate matching of the genotype to the growing conditions to ensure optimal seed quality. Furthermore, the data demonstrated a strong influence of climatic conditions in the year of production, which is crucial for seed vigor.

Keywords: crop production system; wheat; germination; seed storage; seed longevity



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1. Introduction

Wheat is one of the world's most commonly consumed cereal grains. According to the Food and Agriculture Organization of the United Nations (FAO), wheat is and will remain the most important source of food grain for humans. Global wheat production in 2025 was estimated at 793 million tonnes [1]. Due to its immense importance, around 850,000 wheat accessions can be found in ex situ genebank collections worldwide [2]. Genetic resources allow for the breeding and selection of varieties that demonstrate beneficial agricultural traits, such as disease resistance and the ability to adapt to diverse environmental conditions. This is particularly relevant in cultivation systems such as organic farming, where the fundamental objective is to optimise the use of natural resources with minimal external inputs, without negative effects on grain quality [3,4].

The quality of seeds plays an important role in crop production and food security, as well as in the long-term storage of plant genetic resources [5,6]. Production of good quality seeds needs optimal field conditions for a given species; however, very often cultivation require compromises between favorable and specific local environmental conditions. Germination percentage and vigor are important criteria of seed quality. According to the International Seed Testing Association (ISTA, Zurich, Switzerland), vigor is defined as the sum of those properties that determine the activity and performance of seed lots for acceptable germination in a wide range of environments [7]. Rapid and uniform emergence of vigorous seedlings ensures high plant performance that affects uniformity of development, yield, and quality of the harvested product. High-quality seeds are characterized by high viability and produce normal seedlings [8].

Seed longevity, defined as the time during which seeds retain their ability to germinate, is regulated by genetic factors, but is also dependent on non-genetic determinants, such as environmental conditions during seed development and harvest. To assess seed longevity, specific testing protocols have been developed. Among these, the controlled deterioration (CD) test involves the deterioration of seeds in a precise and controlled manner at an elevated moisture content and temperature for a defined period of time. The expression of seed quality indicated by the CD test is a prediction of seed longevity due to a correlation with naturally aged seeds [9,10]. Understanding seed longevity is crucial for optimizing crop production, as it directly affects germination rates and overall yield potential.

The choice of farming system can influence seed performance, both through management practices and environmental interactions. In modern agriculture, three primary farming systems are distinguished: conventional, integrated and ecological. Conventional agriculture is typically practiced on specialized farms implementing intensive production technologies with substantial inputs of industrial resources [11]. Crop production, often including wheat, is sometimes practiced in monoculture due to economic and organizational benefits. In this system, a single crop species is produced in the same field in consecutive years. Monoculture farming has the advantage of simplifying technology, allowing for specialization and responding to high market demand. However, it should be noted that long-term monoculture has been shown to have negative consequences, including soil depletion, increased disease and pest pressure, and the need for intensive use of fertilizers and plant protection products. These factors can ultimately reduce yields and grain quality [12,13]. In contrast, integrated and ecological systems are promoted as environmentally friendly management methods. A system of sustainable plant production requires a limited use of industrial means of production, the use of integrated pest management, and the minimization of the negative impact of agriculture on the natural environment, while simultaneously producing high-quality food [14,15]. Organic farming excludes the use of chemical plant protection products and concentrated mineral fertilizers; limitation of the occurrence of pests, diseases and weeds is ensured by agricultural practices such as crop rotation, tillage, organic fertilization, date and density of sowing, and seed quality, as well as mechanical, biological, and physical methods of plant protection [16].

Research on various management methods focuses mainly on the comparisons of economic effects [17,18], ecological aspects related to the use of pesticides or fertilizer and their environmental consequences [19,20] and quality assessment of the obtained products [21–23].

Despite significant advances in understanding how individual environmental and agronomic factors influence seed vigor and longevity, there is still a lack of knowledge regarding the comprehensive impact of entire production systems. Previous studies have examined, for instance, the influence of climate [24], tillage practices [25], and fertilization strategies [26,27]. Research has also explored the relationship between seed yield, size and vigor [27,28]. However,

it should be noted that most of these findings remain fragmented and do not fully capture the broader role of production systems as a whole in seed vigor and longevity.

Existing publications comparing the effects of different crop production systems on seed germination are still limited. For example, Ref. [29] reported a significant decrease in the vigor and germination of barley when comparing grain from ecological (organic) and conventional systems. However, in other studies, such as [30], the type of crop production system did not have a significant effect on the vigor and germination of winter wheat or spring barley.

To the best of our knowledge, there are no reports comparing comprehensively the effects of different crop production systems on seed germination and storability in wheat. Therefore, the aim of this study is to compare wheat seeds originating from four different farming systems, namely conventional, conventional monoculture, integrated and, organic, with a focus on assessing their germination capacity and the efficacy for long-term storage. A deeper understanding of the role of production systems in shaping seed quality and their suitability for ex situ conservation is of major importance both for agricultural practice and for the preservation of genetic resources.

2. Materials and Methods

2.1. Seed Samples and Crop Production Systems

This study was conducted from 2014 to 2016 at the Agricultural Research Station of the Institute of Soil Science and Plant Cultivation—State Research Institute (IUNG-PIB) in Osiny, Poland (51°28' N, 22°30' E). It has been part of a long-term experiment initiated in 1994 which compares four different crop production systems: (I) conventional (CON)—conditions used for modern farming involving chemical protection and mineral fertilization; (II) conventional monoculture (MONO)—a system involving the cultivation of one crop in the same field for a long time, resulting in a high input of pesticides; (III) integrated (INT)—an approach using natural resources and regulatory mechanisms to ensure sustainable farming; (IV) ecological (ECO)—a system involving limited mineral fertilization and chemical plant protection. Further details are provided in Tables 1 and 2.

Four winter wheat cultivars (Sailor, Jantarka, Arkadia, Bamberka) were cultivated in each system. The tested cultivars were found to have several notable qualities, including higher than average resistance to fungal pathogens and a varied stem and ear morphology. The above traits should make the studied varieties suitable for use in ecological systems. The same sowing standard was used for all varieties, i.e., 450 grains per m². The experiments were set up as one-factor experiments in a randomized block design, with six replications. The area of the plots ranged from 30 to 35 m². Wheat samples from harvests in 2014 and 2016 were used in the study. Seeds from each replication of each cultivar were analyzed separately.

Table 1. Environmental conditions at the experimental location.

Parameter	Description/Value
Complex of agricultural suitability	Very good rye
Soil type	Lessive/grey brown podsolic
Soil textural group	Heavy loamy sand on a clay
Soil richness:	
—Humus	1.4%
—Phosphorus (P ₂ O ₅)	8.6 mg–100 g ^{−1}
—Potassium (K ₂ O)	10.0 mg–100 g ^{−1}
—Magnesium (Mg)	9.1 mg–100 g ^{−1}
—pH (in KCl)	5.9
Forecrop	Clover with grasses
Average annual temperature	7.6 °C
Annual rainfall	587 mm

Table 2. Agronomic management of winter wheat across crop production systems (2014–2016).

Parameter	Conventional	Conventional-Monoculture	Integrated	Ecological
Crop Rotation	Winter rape→Winter wheat→Spring wheat	Winter wheat (continuous cultivation)	Potato→Spring wheat→Faba bean→Winter wheat	Potato→Spring wheat→Red clover→Winter wheat→Oats
NPK Fertilization (kg of pure ingredient per ha)	High N: 170 P: 70 K: 98	High N: 160 P: 70 K: 98	Reduced N: 120 P: 60 K: 80	Natural N: 0 P: 36 K: 75
Type of Fertilizers	Mineral (Ammonium nitrate, Polifoska) + Straw	Mineral + Straw	Mineral + Compost + Catch crops	Ground rock phosphate, Potassium sulphate + Compost
Chemical Protection (Number of treatments)	Intensive (4–5 treatments total)	Very Intensive (5 treatments total)	Limited (3 treatments total)	None (only natural methods)

2.2. Germination Assay and Germination Speed

Germination tests were conducted in two replications of 50 seeds per cultivar, cultivation system and plot. The seeds were placed on moistened filter papers (90 mm round filter, C 160; Munktell & FILTRAK GmbH, Bärenstein, Germany) and then germinated at a constant temperature of 20 °C using a Jacobsen apparatus (Laborset, Łódź, Poland). The number of seedlings showing normal appearance and those showing abnormalities were counted after eight days, in accordance with the ISTA protocol [8]. The results of the germination tests were expressed as the percentage of normal seedlings and the total number of germinated seeds.

To determine the germination speed, the number of germinated seeds (visible radical emergence) was counted daily within the germination period. Four germination-related traits were analyzed. Total germination (TG) was expressed as the percentage of seeds showing radicle emergence and reflected the overall germination capacity of the seed lot. Germination capacity was determined as the final percentage of normal seedlings (NS) at the end of the germination test, as specified by ISTA [8]. The time to reach 50% of total germination (t50) was calculated as the time required for half of the seeds to exhibit radicle emergence, providing an estimate of germination speed. Finally, the area under the curve (AUC) was determined as the integral of the fitted germination curve between $t = 0$ and a defined endpoint (200 h), capturing both the rate and cumulative extent of germination during the germination period.

These parameters, determined using the germination software GERMINATOR [31], enabled a comprehensive evaluation of seed germination performance.

2.3. Assessment of the Relative Storability

The controlled deterioration (CD) test was used to investigate the storage potential of the seed samples, in accordance with the protocol from the Seed Information Database (Royal Botanic Gardens, Kew, Richmond, UK). In order to minimize any change in the moisture content of the seeds, it was first necessary to rehydrate the samples. The seeds were placed into permeable paper bags and held above an 8.7 M unsaturated lithium chloride (LiCl) solution (47% RH) on plastic racks in plastic boxes. The boxes were hermetically sealed and stored in a climatic chamber (Pol-Eko) for seven days at 20 °C [32]. Following a seven-day rehydration period, the seeds were transferred to an ageing chamber set at a temperature of 45 °C and a relative humidity (RH) of 60% (7.1 M LiCl) for 30 days. The time of exposure to the stress condition was selected based on the findings from a preliminary experiment.

2.4. Statistical Analysis

The conformity of the empirical distributions of observed traits with the normal distribution was assessed using the Shapiro–Wilk W-test [33]. Homogeneity of variances was evaluated using Bartlett’s test. Three-way analyses of variance (ANOVA) were conducted to assess the effect of year, system and cultivar as well as their interactions on each trait individually. Arithmetic means and standard deviations were calculated for each trait. Additionally, Fisher’s least significant differences (LSDs) test was estimated at a significance level of $\alpha = 0.05$, and homogeneous groups were identified based on these LSD values. Relationships between the examined traits were evaluated using Pearson correlation coefficients. All statistical analyses and result visualizations were carried out using Gen-stat 23.1 software [34].

3. Results

3.1. The Effect of Tested Parameters on the Germination Traits of Wheat Seed

The analysis of variance (ANOVA) demonstrated that all of the tested parameters (year, crop production system and cultivar) had a significant effect on most of the traits that were evaluated (Table 3).

Table 3. Mean squares from analysis of variance (ANOVA) and significance levels (*p*-values) for factors influencing germination traits of wheat.

Source of Variation	d.f.	NS (%)	TG (%)	t50 (h)	AUC
Year	1	277.5	209.77 **	1062 **	169.5
System	3	136.79	37.7	1851.2 ***	919.6 ***
Cultivar	3	2635.14 ***	424.86 ***	3264.1 ***	2509.6 ***
Year $\times$ System	3	23.78	59.8	517.8 **	246.3
Year $\times$ Cultivar	3	512.81 ***	86.84 *	389.1 *	230.5
System $\times$ Cultivar	9	170.99 *	40.58	851.7 ***	572.3 ***
Year $\times$ System $\times$ Cultivar	9	253.03 **	61.24 *	241.6	242.5 *
Residual	221	82.19	29.32	130.1	102.4

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; d.f.—the number of degrees of freedom. NS (%)—percentage of normal seedlings; TG (%)—percentage of total germination-visible radicle emergence (%); t50 (h)—time to reach 50% of total germination; AUC—area under the germination curve (200 h).

The cultivar had a significant effect ($p < 0.001$) on all germination traits NS (%), TG (%), t50 (h), AUC. The production system significantly influenced the germination speed (AUC, t50), while the year of the experiment influences t50 and TG (%). Furthermore, statistically significant interactions were observed among the factors influencing the examined traits. The year $\times$ production system interaction was significant only for t50. In contrast, cultivar $\times$ year, cultivar $\times$ system, and the three-way interaction were significant for three of the four traits examined. The complete results, incorporating mean values and standard deviations for all factors examined, are presented in Tables 4–6.

3.2. Effect of Production System, Cultivar and Year on Germination on Wheat

The analysis indicated significant differences in germination parameters between the tested cultivars. Bamberka had significantly lower values of both germination capacity (NS%) and the number of germinated seeds (TG%) compared to the other cultivars (Table 4, Figures 1A and 2A).

TG (%) was lowest in Bamberka (90.05%) and significantly higher in the remaining cultivars (above 94%), exceeding $LSD_{0.05} = 8.7$. In the case of NS (%) (Figure 1A), Bamberka exhibited a significantly lower percentage (75.20%) in comparison to the three other cultivars (exceeding 86%), with differences significant at $LSD_{0.05} = 14.6$. No significant differences were observed among the other three cultivars (Arkadia, Jantarka, and Sailor) for total germination (TG%) or the proportion of normal seedlings (NS%).

Table 4. Mean values and standard deviations of NS (%), TG (%), t50 (h) and AUC in relation to cultivar of wheat.

Cultivar		Arkadia	Bamberka	Jantarka	Sailor
Year	System	NS (%)			
2014	CONV	72 ± 12.543 efg	76.5 ± 7.55 defg	87.95 ± 5.392 abcd	87.78 ± 5.245 abcd
	ECO	77.5 ± 5.508 cdefg	77.5 ± 12.477 cdefg	91.52 ± 3.039 abc	93.5 ± 1 ab
	INTGR	84 ± 8.165 abcde	82.37 ± 7.029 abcdef	78 ± 12.166 cdefg	80.16 ± 10.087 abcdefg
	MONO	79.73 ± 14.952 abcdefg	77.5 ± 3.786 cdefg	94.12 ± 3.924 a	87 ± 4.761 abcd
2016	CONV	89.33 ± 8.414 abcd	69.25 ± 15.697 fg	89 ± 7.261 abcd	93.5 ± 4.101 ab
	ECO	93.64 ± 3.443 ab	82.55 ± 9.125 abcdef	87.33 ± 8.752 abcd	85.83 ± 6.74 abcde
	INTGR	87.53 ± 7.646 abcd	66.08 ± 15.448 g	90.83 ± 12.518 abcd	91.17 ± 5.686 abc
	MONO	88.17 ± 5.289 abcd	79.17 ± 13.469 bcdefg	88.33 ± 6.14 abcd	85.86 ± 5.814 abcde
Average		86.72 ± 9.293 A	75.2 ± 13.591 B	88.8 ± 8.607 A	88.59 ± 6.684 A
LSD _{0.05} for interaction: 14.6					
		TG (%)			
2014	CONV	93 ± 3.464 ab	94.5 ± 1.915 ab	95.98 ± 3.266 ab	93.89 ± 4.189 ab
	ECO	96 ± 3.651 ab	97 ± 1.155 ab	98 ± 1.633 a	98.5 ± 1 a
	INTGR	96.5 ± 2.517 ab	94.47 ± 3.792 ab	98 ± 2 a	90.08 ± 4.176 bc
	MONO	99.3 ± 0.879 a	89.5 ± 3.416 bc	98 ± 2.828 a	93.5 ± 1.915 ab
2016	CONV	96.33 ± 3.393 ab	90.64 ± 7.487 abc	95.83 ± 2.329 ab	96.67 ± 3.339 ab
	ECO	97.64 ± 3.075 ab	89.27 ± 4.756 bc	92.33 ± 4.499 abc	90.83 ± 5.006 abc
	INTGR	94.52 ± 4.832 ab	83.81 ± 13.635 c	94.5 ± 9.308 ab	96.33 ± 2.535 ab
	MONO	95.83 ± 2.758 ab	91.33 ± 7.353 abc	92.17 ± 4.783 abc	93.86 ± 2.989 ab
Average		96.09 ± 3.584 A	90.05 ± 8.449 B	94.6 ± 5.455 A	94.31 ± 4.168 A
LSD _{0.05} for interaction: 8.7					
		t50 (h)			
2014	CONV	71.12 ± 1.755 bcdef	77 ± 3.918 bcd	63.74 ± 2.114 defgh	75.53 ± 2.609 bcd
	ECO	59.55 ± 3.982 efgh	68.79 ± 5.146 bcdefgh	56.14 ± 2.326 gh	57.86 ± 2.359 fgh
	INTGR	72.43 ± 14.124 bcde	74.69 ± 3.963 bcd	54.73 ± 4.617 h	69.28 ± 2.699 bcdefg
	MONO	64.44 ± 2.79 cdefgh	65.25 ± 1.989 cdefgh	57.88 ± 2.668 fgh	63.93 ± 1.85 defgh
2016	CONV	70.7 ± 8.419 bcdef	81.76 ± 13.95 b	59.99 ± 7.242 efgh	58.75 ± 5.832 efgh
	ECO	67.08 ± 7.879 cdefgh	70.3 ± 12.745 bcdefg	67.03 ± 13.38 cdefgh	64.03 ± 10.614 defgh
	INTGR	78.93 ± 6.117	109 ± 30.204 a	66.94 ± 6.455 cdefgh	65.7 ± 4.785 cdefgh
	MONO	70.5 ± 6.951 bcdefg	66 ± 20.67 cdefgh	67.75 ± 10.636 bcdefgh	66.19 ± 8.326 cdefgh
Average		70.63 ± 8.66 B	79.32 ± 23.31 A	63.74 ± 9.48 C	64.41 ± 7.87 C
LSD _{0.05} for interaction: 14.508					
		AUC			
2014	CONV	71.44 ± 4.983 efghijk	68.63 ± 5.444 ghijk	81.91 ± 3.59 abcdef	70.03 ± 3.714 fghijk
	ECO	81.8 ± 5.894 abcdef	67.22 ± 10.791 hijk	91.35 ± 4.318a	84.47 ± 3.167 abcd
	INTGR	68.73 ± 15.363 ghijk	65.87 ± 9.508 ijk	86.99 ± 4.149 ab	72.9 ± 2.336 defghijk
	MONO	72.07 ± 9.854 defghijk	70.42 ± 2.768 fghijk	84.22 ± 5.947 abcde	78.79 ± 2.737 abcdefgh
2016	CONV	73.5 ± 8.859 cdefghijk	62.6 ± 10.437 k	84.42 ± 7.775 abcd	86.15 ± 6.862 abc
	ECO	77.95bcdefghij ± 9.043	72.09 ± 12.291 defghijk	75.22 ± 12.411 bcdefghijk	77.25 ± 11.139 bcdefghij
	INTGR	65.19 ± 6.846 jk	47.76 ± 13.165 l	78.69 ± 9.907 abcdefghi	78.45 ± 4.737 bcdefghi
	MONO	73.43 ± 7.1 cdefghijk	80.6 ± 21.418 abcdefg	74.22 ± 11.624 bcdefghijk	76.43 ± 9.043 bcdefghij
Average		72.68 ± 9.27 B	66.24 ± 16.85 C	80.02 ± 10.5 A	78.82 ± 8.41 A
LSD _{0.05} for interaction: 12.871					

Different lowercase letters indicate significant differences between interactions; uppercase letters indicate significant differences between averages ($p < 0.05$).

Table 5. Mean values and standard deviations of observed traits in relation to production system.

System	NS (%)	TG (%)	t50 (h)	AUC
CONV	84.22 ± 12.8 a	94.74 ± 4.663 a	68.81 ± 11.78 b	75.75 ± 11.53 a
ECO	86.71 ± 8.66 a	93.74 ± 5.14 a	65.38 ± 10.49 b	77.09 ± 11.28 a
INTGR	83.29 ± 13.69 b	92.83 ± 8.813 b	77.41 ± 21.54 a	68.76 ± 14.83 b
MONO	85.18 ± 9.15 a	93.74 ± 4.913 a	66.43 ± 11.17 b	76.22 ± 12.14 a
LSD _{0.05}	3.2	1.9	4.037	3.581

Different lowercase letters within a column indicate significant differences among systems at $p \leq 0.05$.

Table 6. Mean values and standard deviations of observed traits in relation to year.

Year	NS (%)	TG%	t50	AUC
2014	83.02 ± 9.7 a	95.35 ± 3.764 a	65.95 ± 8.06 b	75.88 ± 9.85 a
2016	85.45 ± 11.75 a	93.24 ± 6.645 b	70.69 ± 16.69 a	73.99 ± 13.73 a
LSD _{0.05}	2.6	1.6	3.268	2.899

Different lowercase letters within a column indicate significant differences between years at $p \leq 0.05$.

Regarding germination speed, Bamberka showed the slowest rate of germination, as indicated by the highest t50 value (79.32 h) and the lowest AUC (66.24). Jantarka and Sailor exhibited the highest germination speed (t50, AUC) among the tested cultivars, as reflected by the lowest t50 values (63.74, 64.41 h) (Table 4, Figure 1C) and the highest area under the curve (80.02, 78.82) values (Table 4, Figure 1D). Faster germination in these two cultivars suggests greater seed vigor and the potential for more uniform seedling emergence in the field.

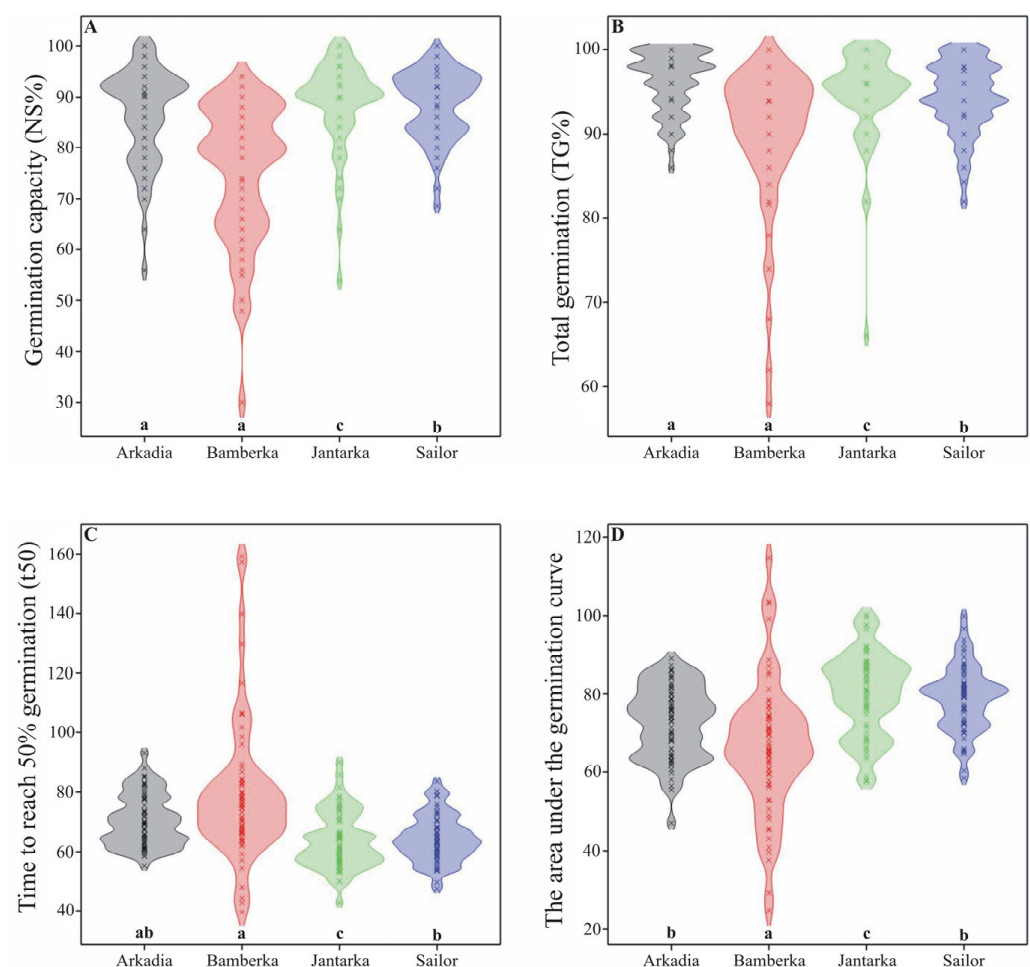


Figure 1. Effect of cultivar on germination parameters of winter wheat. The density plots illustrate the distribution and variability of germination traits across the four winter wheat cultivars. (A) Normal Seedlings (NS %), (B) Total Germination (TG %), (C) time to 50% germination (t50) (D) Area Under the Curve (AUC). Cross symbols (x) represent individual observations. Different lowercase letters (a–c) indicate statistically significant differences between cultivars according to post hoc test at $p \leq 0.05$.

Significant differences were observed among cultivation systems (Table 5, Figure 2). The analysis of variance indicated that the integrated system (INTGR) was significantly different from the other production methods, forming a distinct homogeneous group (Table 5).

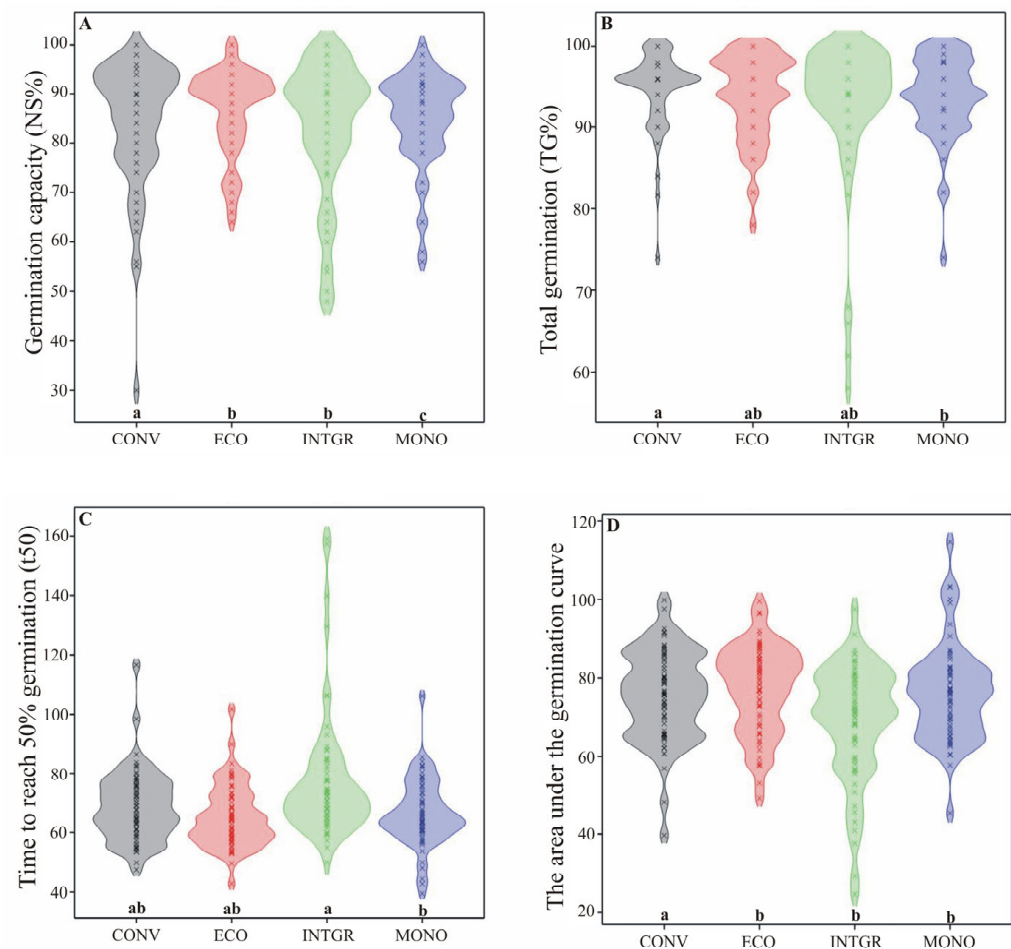


Figure 2. Effect of crop production system on germination parameters of winter wheat. The density plots illustrate the distribution and variability of germination traits across the systems. (A) Normal Seedlings (NS %), (B) Total Germination (TG %), (C) time to 50% germination (t50), (D) Area Under the Curve (AUC). Cross symbols (x) represent individual observations. Different lowercase letters (a–c) indicate statistically significant differences between cropping systems according to post hoc test at $p \leq 0.05$.

While the seeds from the conventional (CONV), ecological (ECO) and monoculture (MONO) systems exhibited high germination (group a), the INTGR system showed a significant, though not considerable, reduction in germination. The difference between these systems (1.91) exceeded the $LSD_{0.05}$ value (1.9). A similar pattern was observed for germination speed. The Integrated system (INTGR) exhibited statistically significant differences compared to the other cropping systems, forming a separate homogeneous group. Specifically, it recorded significantly higher t50 values and lower AUC values (Figure 2C,D), indicating a slower germination rate relative to the CONV, ECO, and MONO systems.

The proportion of normal seedlings NS (%) was slightly higher in 2016 (85.45%) than in 2014 (83.02%) (Table 6, Figure 3A), with the difference again not reaching statistical significance ($LSD_{0.05} = 2.6$).

In contrast, total germination (TG%) was significantly higher in 2014 (95.35%) than in 2016 (93.24%), with the difference of 2.11 percentage points exceeding the $LSD_{0.05}$ value (1.6) (Figure 3B). Proportion of normal seedlings remained relatively stable across years, environmental conditions in 2014 favored a slightly higher overall germination. No significant differences were detected for the AUC trait (Figure 3D), whereas significant differences were identified for t50 (Figure 3C). The lack of significant variation in AUC values indicates that, despite differences in germination timing, overall germination performance and seed lot quality remained stable across years.

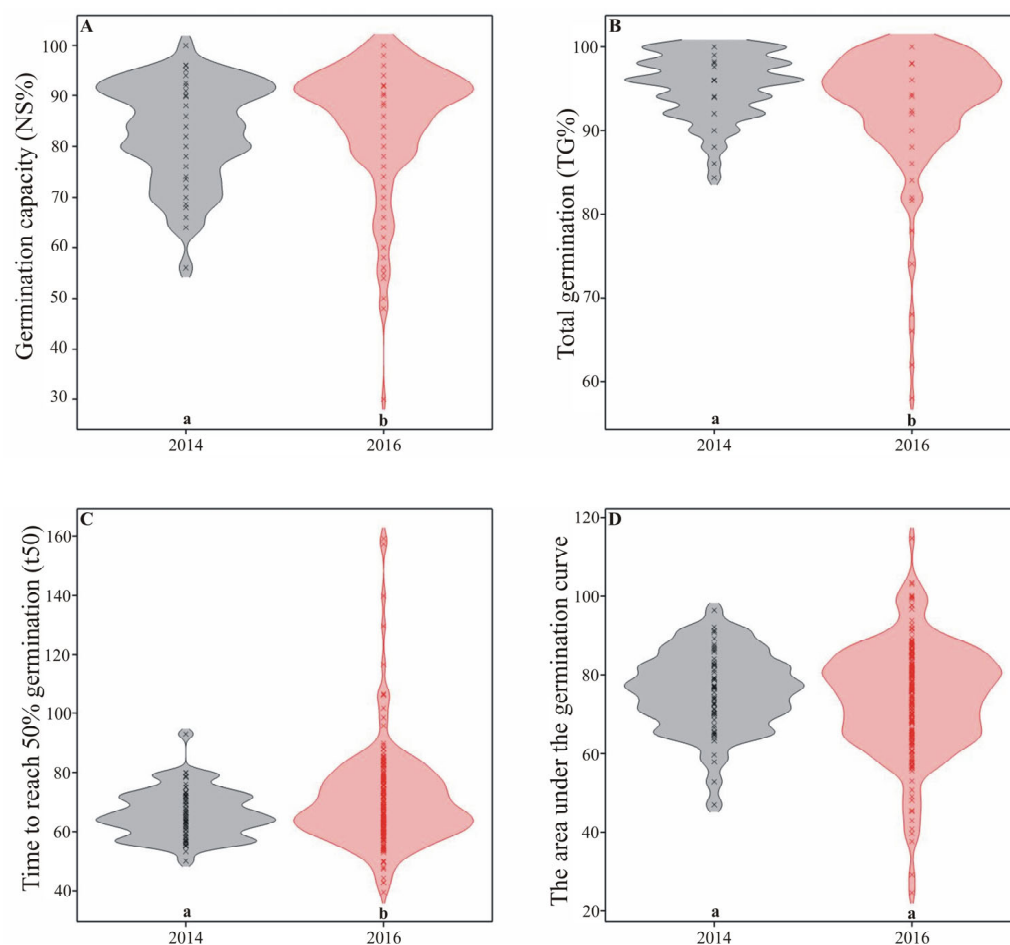


Figure 3. Effect of year on germination parameters of winter wheat. The density plots illustrate the distribution and variability of germination traits between the year. (A) Normal Seedlings (NS %), (B) Total Germination (TG %), (C) time to 50% germination (t50), (D) Area Under the Curve (AUC) Cross symbols (x) represent individual observations. Different lowercase letters (a–b) indicate statistically significant differences between years according to post hoc test at $p \leq 0.05$.

3.3. The Effect of Tested Parameters on the Germination Traits of Wheat Seed Subjected to Controlled Deterioration

The analysis of variance showed that both the main factors and their interactions significantly affected the studied germination traits (Table 7).

Table 7. Mean squares from three-way analysis of variance and levels of significance (p -values) for factors influences germination traits of wheat (CD).

Source of Variation	d.f.	NS (%)	TG (%)	t50 (h)	AUC
Year	1	3764.1 ***	3966.1 ***	60,909.9 ***	2043.6 *
System	3	6326.3 ***	2672.1 ***	1892.7 *	10,285.4 ***
Cultivar	3	10,637.6 ***	21,861.6 ***	36,129.5 ***	28,798.4 ***
Year $\times$ System	3	3747.2 ***	4187.7 ***	1481.8	12,571.6 ***
Year $\times$ Cultivar	3	613.2 *	740.2 *	8391.1 ***	2335.1 ***
System $\times$ Cultivar	9	1716.2 ***	1984.1 ***	6280.3 ***	2523 ***
Year $\times$ System $\times$ Cultivar	9	396.5 *	657.3 **	1368.7 *	951 *
Residual	186	200.6	235.6	565.2	403.9

NS (%)—percentage of normal seedlings; TG (%)—percentage of total germination-visible radicle emergence (%); t50 (h)—time to reach 50% of total germination; AUC—area under the germination curve (200 h). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The effect of year was highly significant ($p < 0.001$) for t50 (h), NS (%) and TG (%), and significant ($p < 0.05$) for AUC. Differences in the germination traits of seeds after a controlled deterioration test suggest that environmental conditions during seed development can influence storability and the ability to maintain vigor during storage.

In contrast to fresh seeds, the production system clearly influenced the preservation of seed sowing quality. The strongest effects observed for AUC, NS (%) and TG (%) ($p < 0.001$), while its effect on t50 (h) was weaker ($p < 0.05$).

Cultivar was identified as the major source of variation across all traits. This confirms that basic resistance to deterioration is a strongly genetically determined trait. Regardless of external conditions, genotype defined the basic ability of seeds to maintain viability.

The year $\times$ system interaction was highly significant for AUC, NS (%) and TG (%) ($p < 0.001$), indicating that the effect of production system on the preservation of seed quality depended on environmental conditions during seed development. In contrast, the effect of year $\times$ system on t50 was not significant, indicating that germination speed under stress was relatively insensitive to the year $\times$ system interaction.

The year $\times$ cultivar interaction was highly significant for t50 ($p < 0.001$), with a weaker, nevertheless still significant effect on NS (%) ($p < 0.05$) and TG (%) ($p < 0.01$), highlighting that genotype-specific differences in storability were modulated by the environmental conditions of each production year. The system $\times$ cultivar interaction was highly significant for all traits ($p < 0.001$), indicating that cultivar responses strongly depended on the cropping system.

The three-way interaction of year, system, and cultivar was statistically significant, although generally weaker than the two-way interactions. The strongest effect was observed for AUC ($p < 0.001$), confirming that this trait was the most sensitive to the combined influence of the studied factors. A moderate significance was observed for TG% ($p < 0.01$), while the effects on t50 and NS (%) were smaller but still significant ($p < 0.05$). These results indicate that the combined influence of environmental conditions, production system, and cultivar was important for germination traits, although its impact was not as pronounced as that of the simpler interactions.

The cultivation system and the cultivar genotype had distinct effects on germination traits. Detailed results, including means and standard deviations for all factors studied, are presented in Tables 8–10.

Table 8. Mean values and standard deviations of NS (%), TG (%), t50 (h) and AUC in relation to cultivar of wheat after CD.

Cultivar		Arkadia	Bamberka	Jantarka	Sailor
Year	System	NS (%)			
2014	CONV	70 $\pm$ 11.75 abc	76.5 $\pm$ 7.55 ab	87.95 $\pm$ 5.39 a	87.78 $\pm$ 5.24 a
	ECO	49.5 $\pm$ 7.19 defg	62.5 $\pm$ 11.24 bcde	4 $\pm$ 2 l	40.5 $\pm$ 17.31 ghi
	INTGR	56.67 $\pm$ 5.03 cdefg	62 $\pm$ 9.93 bcdef	8 $\pm$ 7.21 kl	43.5 $\pm$ 24.02 gh
	MONO	39 $\pm$ 10.13 ghi	43 $\pm$ 9.45 gh	13 $\pm$ 2.58 kl	40 $\pm$ 12.44 ghi
2016	CONV	48 $\pm$ 22.77 efgh	47.45 $\pm$ 25.9 efgh 7	31.33 $\pm$ 8.91 hij	56.73 $\pm$ 24.71 cdefg
	ECO	62.67 $\pm$ 10.73 bcde	64 $\pm$ 10.65 bcde	20.55 $\pm$ 13.03 jkl	24 $\pm$ 17.16 ijk
	INTGR	66.33 $\pm$ 7.74 bcd	54.4 $\pm$ 7.92 cdefg	17 $\pm$ 4.86 jkl	54.8 $\pm$ 11.54 cdefg
	MONO	44 $\pm$ 7.43 fgh	44 $\pm$ 12.88 fgh	12.55 $\pm$ 6.07 kl	22.67 $\pm$ 10.97 ijk
Average		53.93 $\pm$ 16.04 A	54.75 $\pm$ 17.62 A	22.79 $\pm$ 22.47 C	41.16 $\pm$ 24.99 B
LSD _{0.05} for interaction: 18.0					
		TG (%)			
2014	CONV	92 $\pm$ 3.74 abc	94.5 $\pm$ 1.91 ab	95.98 $\pm$ 3.27 a	93.89 $\pm$ 4.19 ab
	ECO	76 $\pm$ 11.78 bcdefg	79.5 $\pm$ 5.26 abcdef	4.67 $\pm$ 1.15 l	64.5 $\pm$ 21.25 fg
	INTGR	81.33 $\pm$ 2.31 abcdef	77 $\pm$ 14.83 abcdefg	12.67 $\pm$ 2.31 kl	66.5 $\pm$ 9 fg

Table 8. Cont.

Cultivar		Arkadia	Bamberka	Jantarka	Sailor
2016	MONO	67.5 ± 8.06 fg	74 ± 6.32 cdefg	15 ± 2.58 jkl	64.5 ± 15.18 fg
	CONV	64.5 ± 22.52 fg	59.64 ± 30.14 gh	38.67 ± 12.5 i	67.82 ± 21.51 fg
	ECO	88.83 ± 9.67 abcd	81.17 ± 7.6 abcdef	34.18 ± 23.25 ij	41.33 ± 24.75 hi
	INTGR	87.33 ± 7.34 abcde	70.4 ± 6.07 defg	22 ± 5.22 ijkl	71.2 ± 10.64 defg
	MONO	68.67 ± 9.92 efg	75.33 ± 8.19 bcdefg	25.27 ± 8.4 ijk	40.17 ± 14.95 hi
Average		77 ± 16.34 A	74.75 ± 17.19 A	31.54 ± 25.01 C	57.81 ± 23.92 B
LSD _{0.05} for interaction: 19.5					
t50 (h)					
2014	CONV	80.61 ± 21.26 b	77 ± 3.92 b	63.74 ± 2.11 bcd	75.53 ± 2.61 b
	ECO	118.25 ± 5.94 a	120.95 ± 2.11 a	0 ± 0 f	119.42 ± 1.75 a
	INTGR	118.45 ± 0.47 a	125.77 ± 9.28 a	0 ± 0 f	124.2 ± 6.62 a
	MONO	122.85 ± 2.79 a	119.2 ± 5.25 a	0 ± 0 f	124.7 ± 6.39 a
2016	CONV	55.08 ± 34.95 bcd	40.39 ± 32.16 cde	61.49 ± 30.26 bcd	66.23 ± 34.94 bcd
	ECO	69.33 ± 8.39 bc	71.78 ± 6.22 b	37.17 ± 43.14 de	41.34 ± 44.34 cde
	INTGR	72.97 ± 3.51 b	81.77 ± 9.65 b	0 ± 0 f	81.95 ± 8.15 b
	MONO	62.01 ± 20.98 bcd	76.36 ± 5.92 b	0 ± 0 f	21.37 ± 36.65 ef
Average		75.82 ± 29.81 AB	78.62 ± 30.55 A	21.52C ± 34.24	65.29 ± 46.48 B
LSD _{0.05} for interaction: 30.28					
AUC					
2014	CONV	108.06 ± 21.63 abc	116.3 ± 6.91 ab	129.99 ± 5.03 a	117.25 ± 5.23 ab
	ECO	64.13 ± 12.41 fgh	64.17 ± 5.2 fgh	1.57 ± 2.71 n	52.87 ± 17.87 ghij
	INTGR	67.36 ± 1.71 efgh	59.72 ± 15.12 ghi	9.87 ± 2 mn	53.2 ± 9.43 ghij
	MONO	54.45 ± 6.73 ghij	61.22 ± 5.46 ghi	12.21 ± 2.28 lmn	52.59 ± 13.52 ghij
2016	CONV	89.87 ± 30.35 cde	78.18 ± 37.28 defg	45.44 ± 17.38 hijk	89.97 ± 28.65 cde
	ECO	94.61 ± 27.2 bcd	105.11 ± 10.81 abc	36.69 ± 25.01 ijkl	47.65 ± 32.19 hijk
	INTGR	108.14 ± 8.98 abc	87.89 ± 9.41 cdef	25.41 ± 5.28 klm	87.42 ± 10.58 cdef
	MONO	91.98 ± 11.58 bcde	95.34 ± 9.68 bcd	29.7 ± 10.53 jklm	51.88 ± 18.82 hij
Average		89.36 ± 25.06 A	87.69 ± 24.98 A	36.64 ± 33.89 C	66.51 ± 31.16 B
LSD _{0.05} for interaction: 25.59					

Different lowercase letters indicate significant differences between interactions; uppercase letters indicate significant differences between averages ($p < 0.05$).

Table 9. Mean values and standard deviations of TG (%) in relation to production system, cultivar and year on wheat after controlled deterioration.

System	NS (%)	TG (%)	t50 (h)	AUC
CONV	57.35 ± 25.27 a	70.27 ± 25.88 a	60.89 ± 30.37 ab	91.15 ± 33.56 a
ECO	42.84 ± 23.95 b	61.39 ± 29.81 ab	64.15 ± 41.42 ab	66.15 ± 36.98 b
INTGR	46.17 ± 22.28 b	61.67 ± 27.02 ab	72.55 ± 47.1 a	65.59 ± 32.8 b 7
MONO	31.84 ± 16.18 c	53.52 ± 23.51 b	54.23 ± 47.4 b	62.21 ± 29.96 b
LSD _{0.05}	10.3	9.3	14.66	13.79

Different lowercase letters within a column indicate significant differences among systems at $p \leq 0.05$.

Table 10. Mean values and standard deviations of observed traits in relation to year on wheat after controlled deterioration.

Year	NS (%)	TG (%)	t50 (h)	AUC
2014	50.6 ± 26.21 a	68.25 ± 28.57 a	88.61 ± 45.21 a	66.6 ± 37.9 a
2016	41.38 ± 22.49 b	58.79 ± 26.17 b	51.31 ± 35.48 b	73.38 ± 34.15 a
LSD _{0.05}	7	8	11.38	10.43

Different lowercase letters within a column indicate significant differences between years at $p \leq 0.05$.

3.4. Effect of Production System, Cultivar and Year on Germination on Wheat Seeds Subjected to Controlled Deterioration

The results indicate that seed storability, evaluated using the controlled deterioration test, is strongly genotype-dependent and reflects inherent differences in seed biology among cultivars. Significant cultivar-dependent differences were observed for both NS (%) (percentage of normal seedlings) (Table 8, Figure 4A) and TG (%) (percentage of total germination) (Table 8, Figure 4B).

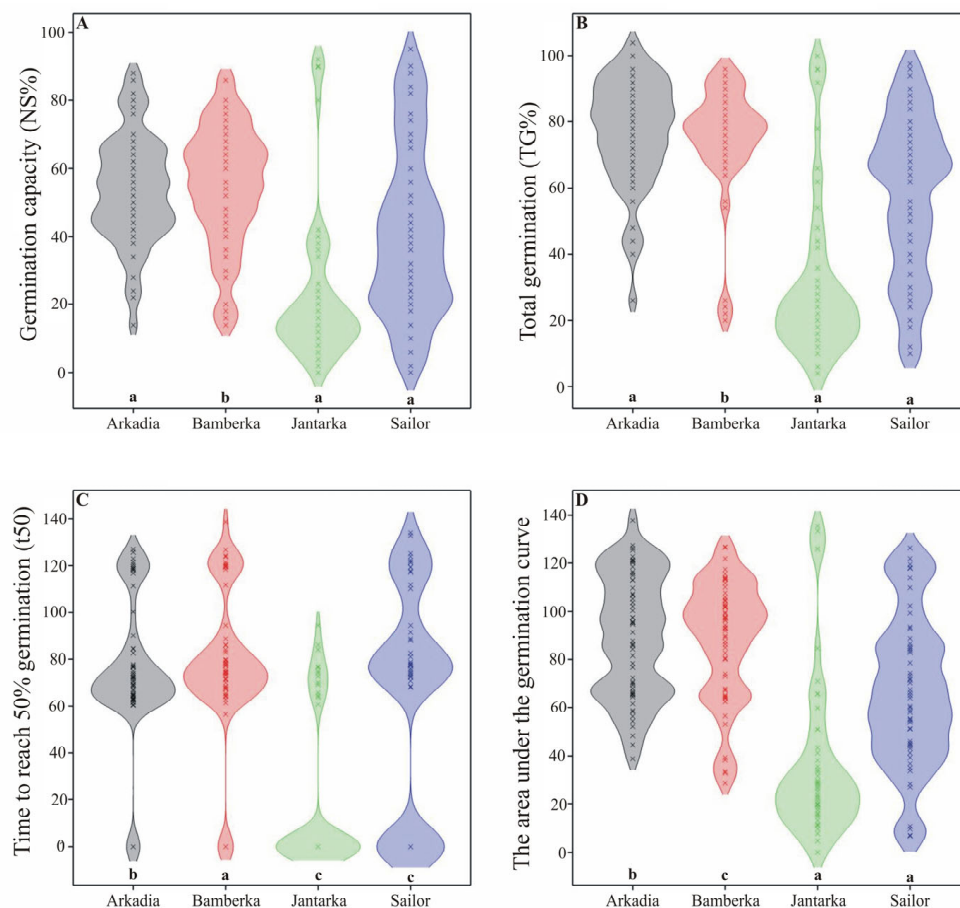


Figure 4. Effect of cultivar on germination parameters of winter wheat after controlled deterioration. The density plots illustrate the distribution and variability of germination traits across the four winter cultivars. (A) Normal Seedlings (NS %), (B) Total Germination (TG %), (C) time to 50% germination (t50) (D), Area Under the Curve (AUC). Cross symbols (x) represent individual observations. Different lowercase letters (a–c) indicate statistically significant differences between cultivars according to post hoc test at $p \leq 0.05$.

Cultivar had a significant effect on germination speed, as reflected by differences in t50 and AUC values, indicating strong genotypic control over the dynamics of the germination process. Regarding the t50 trait, Jantarka was the least robust cultivar (Table 8, Figure 4C), achieving 50% germination only in seeds from the conventional system in 2014, and from both the conventional and organic systems in 2016. The Bamberka variety exhibited the longest duration to 50% germination, with an average of 78.6 h, although this difference was not statistically significant (Figure 4C). The cultivars differed significantly in terms of AUC values (Table 8, Figure 4D). The highest mean values were recorded for Arkadia (89.35) and Bamberka (87.69), while Sailor exhibited intermediate values (66.51) and Jantarka the lowest (36.64) (Figure 4D).

Crop production system had a significant effect on germination of seeds subjected to the controlled deterioration test (Table 9).

The conventional system provided the highest NS (57.35%) and TG (70.27%) (Figure 5A,B), while both the organic and integrated systems produced significantly lower values (42.84–46.17% NS; 61.39–61.67% TG).

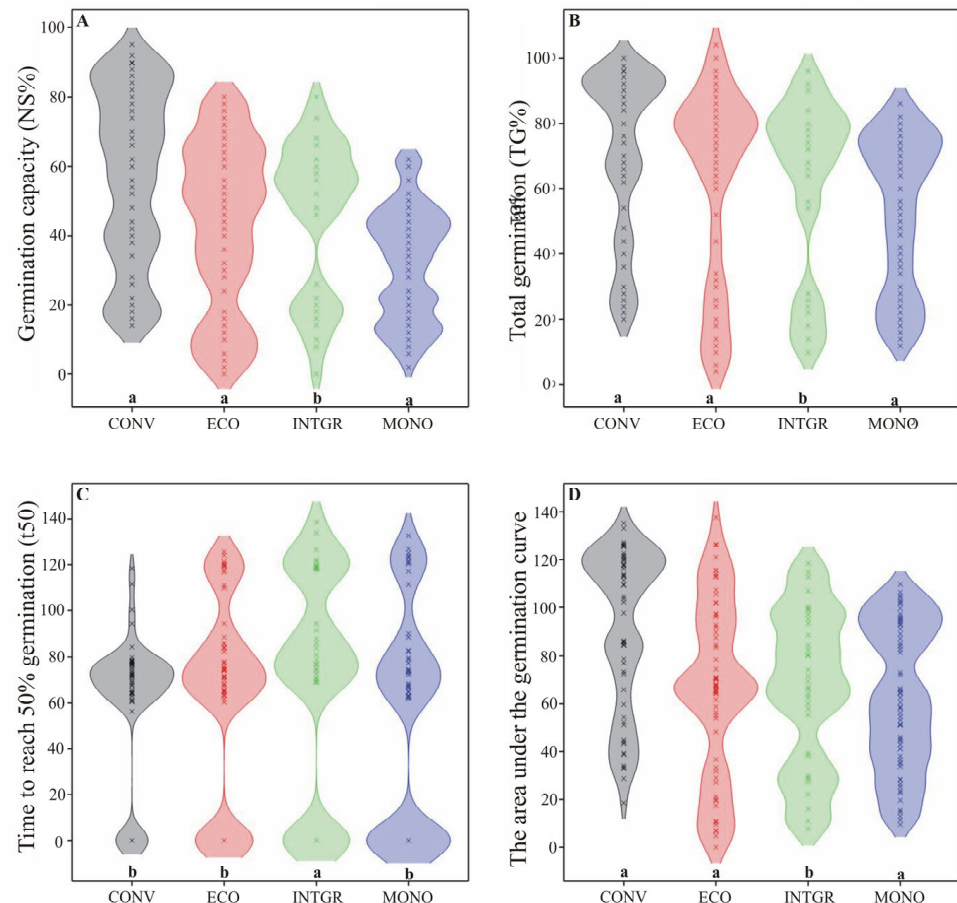


Figure 5. Effect of crop production system on germination parameters of winter wheat after controlled deterioration. The density plots illustrate the distribution and variability of germination traits across the systems. (A) Normal Seedlings (NS%), (B) Total Germination (TG%), (C) time to 50% germination (t50 h), (D) Area Under the Curve (AUC). Cross symbols (×) represent individual observations. Different lowercase letters (a–b) indicate statistically significant differences between cropping systems according to post hoc test at $p \leq 0.05$.

The monoculture system produced the lowest quality seed (31.84% NS, 53.52% TG). The most pronounced decrease in t50 was recorded in the MONO system (−52 h), whereas t50 values in the CONV system demonstrated the greatest stability over the study period, with the least variation (−19 h). The highest AUC values were observed in the conventional system (CONV: 91.15 ± 33.56), whereas the lowest were recorded in the monoculture system (MONO: 62.21 ± 29.96) (Figure 5C,D). The ECO and INTGR systems demonstrated intermediate values of 66.16 and 65.59, respectively (Figure 5D). Seeds produced under the conventional system may germinate faster and more uniform under field conditions, whereas seeds from monoculture or less intensive systems may have reduced vigor and germinate less uniformly.

Year-to-year variation had a significant impact on seed germination indicating that environmental conditions during seed development may influence seed storability (Table 10, Figure 6).

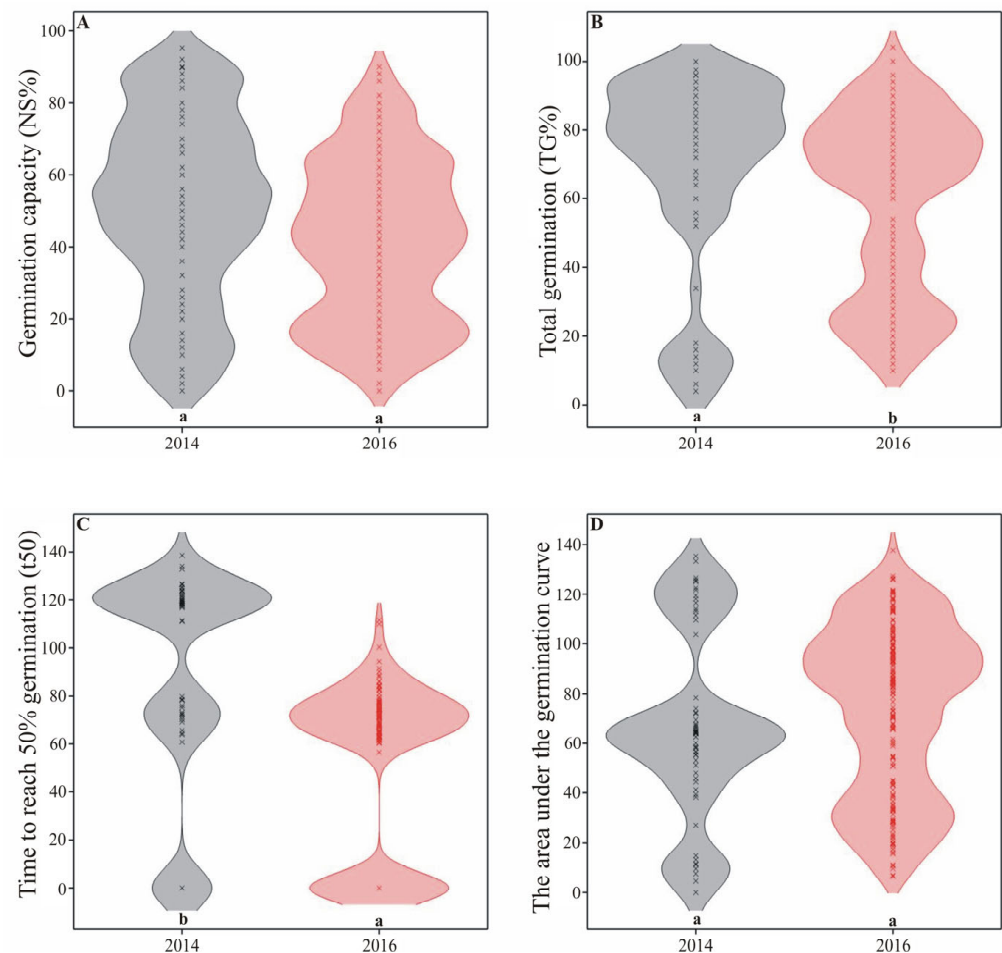


Figure 6. Effect of year on germination parameters of winter wheat after controlled deterioration. The density plots illustrate the distribution and variability of germination traits across the year (A) Normal Seedlings (NS %), (B) Total Germination (TG %), (C) time to 50% germination (t50), (D) Area Under the Curve (AUC). Cross symbols (×) represent individual observations. Different lowercase letters (a–b) indicate statistically significant differences between years according to post hoc test at $p \leq 0.05$.

In 2014, the mean values of NS (50.6%) and TG (68.3%) exhibited higher values when compared with those observed in 2016 (41.4% NS, 58.8% TG) (Figure 6A,B).

A statistically significant decrease in t50 was observed in 2016 (51.3 h on average) compared to 2014 (88.6 h on average) (Figure 6C, Table 10). Although seeds produced in 2016 showed a significantly lower t50, indicating faster germination after controlled deterioration, this was not accompanied by a significant increase in AUC. This suggests a faster but less stable germination process, as reflected by reduced NG% and TG%, whereas seeds produced in 2014 germinated more slowly but with greater physiological stability. Seeds produced under the drier conditions of 2016 were more susceptible to aging than seeds produced in 2014, when environmental conditions were more favorable.

Statistically significant correlations were observed between all pairs of observed traits, both in the control and after controlled deterioration (Table 11).

Three pairs of traits (AUC-NS%, AUC-TG%, and TG-NS%) were characterized by a positive correlation in both conditions considered (Table 11). However, AUC-t50, NS%-t50, and TG%-t50 showed negative correlation in the control and positive correlation after controlled deterioration (Table 11).

Table 11. The correlation matrix for the traits studied in control (above diagonal) and after controlled deterioration (below diagonal).

Trait	AUC	t50 (h)	NS (%)	TG (%)
AUC	1	−0.85 ***	0.43 ***	0.33 **
t50 (h)	0.47 ***	1	−0.28 *	−0.34 **
NS (%)	0.86 ***	0.58 ***	1	0.35 **
TG (%)	0.90 ***	0.72 ***	0.89 ***	1

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

4. Discussion

The quality of seeds is a key factor in the success of agricultural production and genetic conservation efforts. Seeds with a high biological value (i.e., those with high germination capacity, energy and viability) ensure uniform and healthy emergence, thus resulting in stable yields and efficient use of inputs.

The objective of the present study was to examine the predisposition of seeds originating from diverse crop production systems for long-term storage. For this purpose, the controlled deterioration test was selected as an indicator of seed storability. This study examined how different cultivation systems—conventional (CONV), ecological (ECO), integrated (INTGR) and monoculture (MONO)—affect the germination parameters of four winter wheat cultivars (Arkadia, Bamberka, Jantarka and Sailor) over two years (2014 and 2016). The germination parameters assessed included the following: the normal seedling percentage (NS%), the total germination percentage (TG%) and the speed of germination (the time taken to reach 50% of germination, t50; area under the germination curve, AUC).

The study demonstrated that seed germination traits were significantly influenced by cultivar, cropping system and year of research.

Among the assessed parameters, germination speed was especially sensitive to genetic background. Jantarka and Arkadia exhibited the most favorable characteristics, including rapid germination and the highest values of normal seedlings NS (%) and total germination (TG%) in fresh seeds. In contrast, Bamberka consistently demonstrated weaker performance across systems, confirming substantial genotypic variation in seed quality. However, in the controlled deterioration test, the situation was reversed. Jantarka exhibited markedly reduced germination parameters regardless of the production system, whereas Bamberka and Arkadia consistently exhibited higher germination speed and NS% and TG% values. These cultivar-specific responses indicate that seed degradation progresses at different rates depending on the genotype.

This observation supports the theory that seed longevity is genetically determined, with wheat cultivars showing distinct aging kinetics, consistent with the results of [35], who reported significant genotypic variability in viability loss during storage. Some research has shown that seed longevity in wheat is a genetically controlled quantitative trait, with multiple loci influencing tolerance to deterioration [36–38]. The differences in the rate of aging observed among cultivars in this study may also be related to cultivar-specific physiological and biochemical responses to seed deterioration, including metabolic and enzymatic pathways associated with oxidative stress and energy metabolism, as suggested by data reported in the literature [39,40].

The effect of the crop production system was also highly significant for germination parameters. Fresh seeds produced under the ecological system generally showed higher initial germination speed and normal seedling production, but differences among systems were not always statistically significant. Notably, germination speed was significantly higher in the ecological system than in the integrated system (INTGR) ($p < 0.05$). However, no statistically significant differences were found when comparing the ecological system to the conventional (CONV) and monoculture (MONO) systems ($p > 0.05$). By contrast,

although the ecological system produced the highest mean percentage of normal seedlings, these differences were not statistically significant compared to those from any of the other cultivation systems. This suggests that, although organic practices may accelerate the initial stages of germination, they do not guarantee a higher overall success rate of seedling development and are statistically comparable to other systems.

Some studies [41,42] indicated that organic and low-input systems may compromise seed vigor due to increased pathogen pressure, nutrient limitations, and less favorable maturation conditions. Our results are opposite and highlight the potential of organic farming to achieve good germination traits, provided optimal growing conditions are met. It has also been emphasized that the quality of organic seed can be comparable to that of conventionally produced seed when appropriate agronomic practices and suitable cultivars are selected. However, it should be noted that organic seed may remain more susceptible to pathogens [43]. The lack of statistically significant differences between the remaining production systems is also valuable information. This indicates that differences in production systems do not always translate into statistically significant differences in seed sowing quality.

In the controlled deterioration test, however, the influence of the cultivation system on germination parameters was significant. The conventional system (CONV) demonstrated the highest levels of stress resistance and stability for the germination traits that were studied. This indicates that seeds from this system exhibit the best storage potential. High quality may be attributed to the minimization of environmental stresses and pathogen pressure through the implementation of precise agronomic techniques. In turn, monoculture (MONO) leads to the production of seeds of the worst quality, which are completely unsuitable for long-term storage, probably as a result of plant stress (diseases and soil quality, crop infestation by weeds [44,45]).

The significant system $\times$ variety interaction observed for all germination traits, both in fresh seed and after controlled deterioration, indicates that seed performance is strongly genotype-dependent and varies across production systems. From a farmer's perspective, the significant system $\times$ variety interaction means that varieties can be selected and matched to the cultivation system in which they perform best. In contrast, gene banks regenerate and preserve the full spectrum of genetic resources. This also underscores the need for careful monitoring of seed germination during storage and for tailored regeneration strategies, as some genotypes may maintain viability for long periods, while others require more frequent regeneration to safeguard long-term conservation. The importance of our finding is reinforced by the broader literature on seedbanks and conservation, which emphasizes that seed longevity is strongly genotype-dependent and influenced by production conditions.

The CD test also highlighted the importance of weather conditions in a given year. The study showed that germination parameters in 2014 were significantly higher than those in 2016, indicating the strong influence of the climatic conditions, suggesting that weather during seed filling and maturation played a decisive role. This result confirms that even within the same system and the same variety, seed vigor will vary depending on the conditions under which seeds are produced. Our study results confirm the observations of [46], who noted a significant effect of year on spring wheat yield in various production systems conducted at the same experimental station in 2014–2016. In 2014, spring wheat yields were significantly higher than in 2016, primarily due to more favorable weather conditions, namely higher rainfall during the growing season. These observations are supported by the IUNG-PIB report on agricultural drought, which indicates that there is no threat of drought in wheat cultivation in 2014, while periods of water shortage were noted in 2016 [47]. These results emphasize the importance of climatic conditions in a given production year on seed vigor, regardless of the cultivation system.

Overall, the results demonstrate that seed quality assessed under optimal conditions does not fully predict seed performance after aging. While fresh seed germination was largely comparable across production systems, differences in storability became evident only after exposure to controlled deterioration. These findings highlight the importance of combining standard germination tests with aging assays when evaluating seed quality for storage, seed multiplication, and genetic resource conservation.

5. Conclusions

Cultivar was the main factor influencing seed germination performance. However, an inverse relationship was observed between initial germination speed and long-term storability. The faster-germinating cultivar Jantarka was more sensitive to aging stress, whereas slower-germinating cultivars like Bamberka exhibited relatively higher storage potential.

There were only minor differences among the production systems in the fresh seeds; however, these differences became more evident under ageing conditions. The crop production system strongly influences seed storability potential. The conventional system ensured the highest stability against deterioration, whereas monoculture significantly accelerated the loss of viability during aging.

Cultivar responses to production systems varied. Bamberka maintained stable performance across systems, whereas Jantarka appeared more sensitive and may require optimized agronomic conditions.

Climatic conditions in a given year had a significant impact on seed vigor, as evidenced by the higher seed quality in 2014 (no threat of drought) compared to 2016 (water shortages).

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References

1. FAOSTAT. 2025. Available online: <https://www.fao.org/worldfoodsituation/csdb/en> (accessed on 27 September 2025).
2. King, J.; Dreisigacker, S.; Reynolds, M.; Bandyopadhyay, A.; Braun, H.; Crespo-Herrera, L.; Crossa, J.; Govindan, V.; Huerta, J.; Ibba, M.I.; et al. Wheat genetic resources have avoided disease pandemics, improved food security, and reduced environmental footprints: A review of historical impacts and future opportunities. *Glob. Change Biol.* **2024**, *30*, e17440. [\[CrossRef\]](#)
3. Schrama, M.; De Haan, J.; Kroonen, M.; Verstegen, H.; Van der Putten, W. Crop yield gap and stability in organic and conventional farming systems. *Agric. Ecosyst. Environ.* **2018**, *256*, 123–130. [\[CrossRef\]](#)
4. Salgotra, R.K.; Chauhan, B.S. Genetic diversity, conservation, and utilization of plant genetic resources. *Genes* **2023**, *14*, 174. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Finch-Savage, W.E. Influence of seed quality on crop establishment, growth, and yield. In *Seed Quality*; CRC Press: Boca Raton, FL, USA, 2020; pp. 361–384.
6. Solberg, S.Ø.; Yndgaard, F.; Andreassen, C.; Von Bothmer, R.; Loskutov, I.G.; Asdal, Å. Long-term storage and longevity of orthodox seeds: A systematic review. *Front. Plant Sci.* **2020**, *11*, 1007. [\[CrossRef\]](#) [\[PubMed\]](#)
7. ISTA. *International Rules for Seed Testing*; International Seed Testing Association: Bassersdorf, Switzerland, 2024.
8. Finch-Savage, W.E.; Bassel, G.W. Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **2016**, *67*, 567–591. [\[CrossRef\]](#)

9. Powell, A.A.; Matthews, S. Towards the validation of the controlled deterioration vigour test for small seeded vegetables. *Seed Test. Int.* **2005**, *129*, 21–24.
10. Marcos Filho, J. Seed vigor testing: An overview of the past, present and future perspective. *Sci. Agric.* **2015**, *72*, 363–374. [CrossRef]
11. Sumberg, J.; Giller, K.E. What is ‘conventional’ agriculture? *Glob. Food Secur.* **2022**, *32*, 100617. [CrossRef]
12. Woźniak, A.; Haliniarz, M. Response of winter wheat to 35-year cereal monoculture. *Agriculture* **2025**, *15*, 489. [CrossRef]
13. Sieling, K.; Stahl, C.; Winkelmann, C.; Christen, O. Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany. *Eur. J. Agron.* **2005**, *22*, 71–84. [CrossRef]
14. FAO. Crop and Grassland Service. Integrated Crop Management. 2025. Available online: <https://policycommons.net/artifacts/18271419/integrated-crop-management/19171545/> (accessed on 20 October 2025).
15. Hussain, M.; Ul-Allah, S.; Farooq, S. Integrated crop management in sustainable agriculture. *Agriculture* **2023**, *13*, 954. [CrossRef]
16. Kociszewski, K. Perspectives of Polish organic farming development in the aspect of the European Green Deal. *Ekon. Sr.* **2022**, *81*, 154–167. [CrossRef]
17. Bilsborrow, P.; Cooper, J.; Tétard-Jones, C.; Średnicka-Tober, D.; Barański, M.; Eyre, M.; Schmidt, C.; Shotton, P.; Volakakis, N.; Cakmak, I.; et al. The effect of organic and conventional management on the yield and quality of wheat grown in a long-term field trial. *Eur. J. Agron.* **2013**, *51*, 71–80. [CrossRef]
18. Feledyn-Szewczyk, B.; Kopiński, J. Productive, environmental and economic effects of organic and Conventional Farms—Case Study from Poland. *Agronomy* **2024**, *14*, 793. [CrossRef]
19. Harasim, E.; Feledyn-Szewczyk, B. Biodiversity assessment of segetal flora, earthworms and terrestrial invertebrates in various agricultural production systems and crops. *Agron. Sci.* **2023**, *78*, 63–75. [CrossRef]
20. Boschiero, M.; De Laurentiis, V.; Caldeira, C.; Sala, S. Comparison of organic and conventional cropping systems: A systematic review of life cycle assessment studies. *Environ. Impact Assess. Rev.* **2023**, *102*, 107187. [CrossRef]
21. Kowalska, I.; Soluch, A.; Mołdoch, J.; Jończyk, K. The effect of farming systems and cultivars on the qualitative and quantitative composition of bioactive compounds in winter wheat (*Triticum aestivum* L.). *Molecules* **2025**, *30*, 902. [CrossRef]
22. Knuth, D.; Gai, L.; Silva, V.; Harkes, P.; Hofman, J.; Šudoma, M.; Bílková, Z.; Alaoui, A.; Mandrioli, D.; Pasković, I.; et al. Pesticide residues in organic and conventional agricultural soils across Europe: Measured and predicted concentrations. *Environ. Sci. Technol.* **2024**, *58*, 6744–6752. [CrossRef]
23. Mitura, K.; Cacak-Pietrzak, G.; Feledyn-Szewczyk, B.; Szablewski, T.; Studnicki, M. Yield and grain quality of common wheat (*Triticum aestivum* L.) depending on the different farming systems (organic vs. integrated vs. conventional). *Plants* **2023**, *12*, 1022. [CrossRef]
24. Probert, R.; Adams, J.; Coneybeer, J.; Crawford, A.; Hay, F. Seed quality for conservation is critically affected by pre-storage factors. *Aust. J. Bot.* **2007**, *55*, 326–335. [CrossRef]
25. Winkler, J.; Kopta, T.; Ferby, V.; Neudert, L.; Vaverková, M.D. Effect of tillage technology systems for seed germination rate in a laboratory tests. *Environments* **2022**, *9*, 13. [CrossRef]
26. Shahzaman, M.; Ishtiaq, M.; Azam, A. Effect of different fertilizers on seed germination and seedling growth of sunflower (*Helianthus annuus* L.) from district Bhimber of Azad Jammu and Kashmir, Pakistan. *Int. J. Bot. Stud.* **2017**, *2*, 10–15.
27. Kristó, I.; Vályi-Nagy, M.; Rácz, A.; Irmes, K.; Szentpéteri, L.; Jolánkai, M.; Kovács, G.P.; Fodor, M.Á.; Ujj, A.; Valentinyi, K.V.; et al. Effects of nutrient supply and seed size on germination parameters and yield in the next crop year of winter wheat (*Triticum aestivum* L.). *Agriculture* **2023**, *13*, 419. [CrossRef]
28. Ambika, S.; Manonmani, V.; Somasundar, G. Review on effect of seed size on seedling vigour and seed yield. *Res. J. Seed Sci.* **2014**, *7*, 31–38. [CrossRef]
29. Panasiewicz, K.; Koziara, W.; Krawczyk, R. Comparison of grain sowing quality and vigor of spring barley. *J. Res. Appl. Agric. Eng.* **2010**, *55*, 42–45.
30. Panasiewicz, K.; Koziara, W.; Sulewska, H.; Krawczyk, R. Sowing quality and vigor of winter wheat grain, growing in accordance with the organic and conventional system. *J. Res. Appl. Agric. Eng.* **2011**, *56*, 58–61.
31. Joosen, R.V.L.; Kodde, J.; Willems, L.A.J.; Ligterink, W.; Van Der Plas, L.H.W.; Hilhorst, H.W. GERMINATOR: A software package for high-throughput scoring and curve fitting of *Arabidopsis* seed germination. *Plant J.* **2010**, *62*, 148–159. [CrossRef]
32. Hay, F.; Adams, J.; Manger, K.; Probert, R. The use of non-saturated lithium chloride solutions for experimental control of seed water content. *Seed Sci. Technol.* **2008**, *36*, 737–746. [CrossRef]
33. Shapiro, S.S.; Wilk, M.B. An analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. [CrossRef]
34. VSN International. *VSN International Genstat for Windows*, 23rd ed.; VSN International: Hemel Hempstead, UK, 2023.
35. Nagel, M.; Börner, A. The longevity of crop seeds stored under ambient conditions. *Seed Sci. Res.* **2010**, *20*, 1–12. [CrossRef]
36. Zuo, J.H.; Chen, F.Y.; Li, X.Y.; Xia, X.C.; Cao, H.; Liu, J.D.; Liu, Y.X. Genome-wide association study reveals loci associated with seed longevity in common wheat (*Triticum aestivum* L.). *Plant Breed.* **2020**, *139*, 295–303. [CrossRef]

37. Arif, M.A.R.; Agacka-Mołdoch, M.; Qualset, C.O.; Börner, A. Mapping of additive and epistatic QTLs linked to seed longevity in bread wheat (*Triticum aestivum* L.). *Cereal Res. Commun.* **2022**, *50*, 709–715. [CrossRef]
38. Yang, Z.; Wu, J.; Wang, Q.; Chen, W.; Shi, H.; Shi, Y.; Yang, J.; Li, N.; Sun, D.; Jing, R. QTL mapping for seed vigor-related traits under artificial aging in common wheat in two introgression line (IL) populations. *PeerJ* **2024**, *12*, e17778. [CrossRef] [PubMed]
39. Groot, S.P.; Van der Wolf, J.M.; Jalink, H.; Langerak, C.J.; van den Bulk, R.W. Challenges for the production of high quality organic seeds. *Seed Test. Int.* **2004**, *127*, 12–15.
40. Yang, Z.; Chen, W.; Jia, T.; Shi, H.; Sun, D. Integrated transcriptomic and metabolomic analyses identify critical genes and metabolites associated with seed Vigor of common wheat. *Int. J. Mol. Sci.* **2023**, *25*, 526. [CrossRef]
41. Nagel, M.; Seal, C.E.; Colville, L.; Rodenstein, A.; Un, S.; Richter, J.; Pritchard, H.W.; Börner, A.; Kranner, I. Wheat seed ageing viewed through the cellular redox environment and changes in pH. *Free. Radic. Res.* **2019**, *53*, 641–654. [CrossRef]
42. Góral, T.; Łukanowski, A.; Małuszyńska, E.; Stuper-Szablewska, K.; Buśko, M.; Perkowski, J. Performance of winter wheat cultivars grown organically and conventionally with focus on *Fusarium head blight* and *Fusarium trichothecene* toxins. *Microorganisms* **2019**, *7*, 439. [CrossRef]
43. Capouchova, I.; Konvalina, P.; Stehno, Z.; Prokinova, E.; Janovska, D.; Honsova, H.; Blaha, L.; Kas, M. Organic cereal seed quality and production. In *Organic Farming and Food Production*; IntechOpen: London, UK, 2012; pp. 25–45. Available online: <https://www.intechopen.com/chapters/40285> (accessed on 20 October 2025).
44. Woźniak, A. Effect of crop rotation and cereal monoculture on the yield and quality of winter wheat grain and on crop infestation with weeds and soil properties. *Int. J. Plant Prod.* **2019**, *13*, 177–182. [CrossRef]
45. Jankowski, K.J.; Kijewski, L.; Dubis, B. Milling quality and flour strength of the grain of winter wheat grown in monoculture. *Rom. Agric. Res.* **2015**, *32*, 191–200.
46. Feledyn-Szewczyk, B.; Jończyk, K.; Stalenga, J. The Effect of Crop Production Systems and Cultivars on Spring Wheat (*Triticum aestivum* L.) Yield in a Long-Term Experiment. *Agriculture* **2024**, *14*, 625. [CrossRef]
47. ADMS—Agricultural Drought Monitoring System. Available online: <https://susza.iung.pulawy.pl/en/index/> (accessed on 20 October 2025).

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