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RESEARCH

The Effect of Seed Moisture Content of Hybrid Maize at Harvest Time on Seed Germination Traits and Antioxidant Enzymes Activity under Simulated Environmental Stresses with Silicon Foliar Application

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Abstract

Seed quality of hybrid maize is affected by different factors, including maturity time and environmental conditions of plant growth. In this study, the effect of four maturity times of hybridized maize from male and female plants was investigated in terms of grain moisture content (30, 35, 40 and 45%) with silicon foliar spraying in a field with saline soil in Kermanshah, Iran. The experiments were on maize seed vigor using the standard germination and simulated tests of cold, Hiltner brick gravel and germination test under drought stress conditions. The results showed that highest percentage and rate of germination were obtained from the treatment with 30% moisture content at maturity with silicon spraying (99% and 0.037 germination per hour). Brick gravel and drought stress tests reduced germination percentage compared to the standard test. Based on Guasnr model, the nonlinear model of germination response curve was fitting to the percentage of moisture contents at maturity time and silicon application for various tests. The activity of Catalase, Ascorbate peroxidase and Malone Dialdehyde enzymes in different tests increased with 35% seed moisture content at the time of harvest and silicon foliar spraying. On the other hand, the maximum activities of the Antioxidant enzymes were found in the germination test under drought stress conditions in the amount of 36.6 μmolmin^{-1}mgprotein Catalase and 2829 nmolmin^{-1}mg Ascorbate peroxidase. In general, according to the decrease in the slope of the germination curve, 30–35% moisture content at maturity time along with silicon use was found to be suitable for producing high quality maize seeds in simulated tests of environmental stresses.

Keywords Catalase · Corn · Kernel · Maturity time · Test · Vigor · Si

1 Introduction

Zea mays L. is one of the most important crops grown in many countries around the world. This plant with a global annual production of 1,235,730,000 tons, is the largest produced cereal crop in the world [1]. Considering the prediction that the world's food production will be limited to 9 billion people by 2050, maize has the potential to help meet the food demand of developing countries. Therefore, it is important to recognize factors that affect crop quality and production of maize [2].

Crop quality and production depend on several factors including seed quality [3]. The three most important criteria for evaluating seed quality are germination ability, vigor, and health. According to the International Seed Testing Association [4], seed vigor is a set of properties of a seed that determine the potential level of seed activity and efficiency during germination [5]. Seed maturation is one of the main factors of seed quality and a prerequisite for successful germination and emergence. Environmental factors viz. soil fertility, soil water content, photoperiod, temperature and position of the seed in the inflorescence or on the mother plant also affect the process of seed development and maturation [6]. Seed quality is influenced by the moisture content of the seed during harvest as well as environmental factors. Indeed, these factors are interrelated. In

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the interest of high crop yields, it is important to investigate these factors [5].

Seed maturity has a significant effect on seed quality as drying during seed maturity is an integral part of seed germination. The reduction in seed moisture content after physiological maturity stage (i.e., maturity for harvest) increases seed vigor. Therefore, optimal moisture content will improve germination percentage and seed quality. Seed quality is also improved by timely harvesting. Harvesting too early can have a negative effect on germination and can reduce seed vigor [7]. Seeds of many plants can germinate shortly after the formation of the embryo, but seed harvest at this stage due to insufficient accumulation of reserve materials during grain filling leads to loss of yield and reduction of seed quality [8]. On the other hand, harvesting too late can also significantly reduce seed quality due to seed aging, undesired environmental factors, or seed damage to the embryo during harvest. Therefore, determining the right harvest time can have a significant impact on the quality of plant seeds [7].

The simplest evaluations to determine seed quality can be performed using a standard germination test. However, this test does not account for environmental stressors in the field resulting in unreliable estimates. Therefore, different tests along with standard germination test can provide a more complete estimate of quality [9].

Seed vigor can be evaluated by tests that artificially create field environmental conditions. Alzahrani et al. [10] determine seed germination as well as seedling emergence under field conditions. Among these tests, only a limited number are acceptable by seed experts and seed testing institutes. These tests include the standard germination, low temperature germination, brick gravel and germination under drought stress tests.

Many climates of the world are experiencing drought [11]. The investigations have showed that drought stress decrease seed germination and limit plant growth. The use of silicon as the second main element of the earth's crust has been effective in improving the negative effects of abiotic stresses such as drought and salinity [12]. The application of Silicon to improve plant tolerance against drought has been reported in a number of crops including rice [13], sorghum [14], corn [15], wheat [16], sunflower [17] and soybean [18]. The silicon foliar application creates drought tolerance in plants by improving the activity of various enzymes and increasing physiological growth and dry matter production [13]. The silicon is beneficial to prevent transpiration losses and improve many physiological and biochemical processes in crops. Hamayoun et al. [19] showed that silicon affects several processes. It improves the water condition of crops, increases photosynthetic activities and helps to strengthen the structure of leaf organs. The protective role of Si against oxidative damage has been documented in various crops [20].

The study of seed moisture content in harvest time and silicon use in saline soil provides the possibility of producing seeds with the desired quantity and quality. Previous studies on stress tolerance and the importance of timely harvesting based on seed moisture content have all shown improved seed quality. However, there is a lack of scientific knowledge about the combined effect of seed moisture and stress factors and application of silicon in saline soil on plant seed vigor. This investigation aims to provide maize seed producers with insights for better harvest time management under various stress conditions.

2 Materials and Methods

2.1 Experimental Treatments

An experiment on hybrid maize was conducted in three replications during year of 2022 in Kermanshah, Iran (34°-18′ N, 47°- 4′ E and altitude of 1420 m above sea level). In this experiment, the treatments included four harvest times of hybrid maize in terms of grain moisture content (30, 35, 40 and 45%) and with silicon foliar spraying (control and silicon). Besides, the effect of these treatments on maize seed vigor was investigated using the tests, such as standard germination, cold, brick gravel and germination under drought stress tests.

The soil of the experimental farm was salty and according to the soil test results, EC was reported as 6.01 $dS.m^{-1}$ and pH as 7.92. The silicon was applied in three stages of plant growth including 3–4 leaf stage, the beginning of flowering and at the time of cob formation as a foliar application with the recommended concentration (200 mg/liter) [19, 20]. Foliar application was done using a manual sprayer (pressure of 20 kPa) and the leaves were completely wet. Deionized water was used with non-ionic surfactant to increase the efficiency of foliar application. The non-ionic surfactant of Nutrica company was made in Iran with product ID Gp-24905 (concentration 0.05%).

2.2 Performing the Experiment

In this study, the hybrid maize seeds of male and female from cultivar of AS71 (each on the appropriate planting date) were planted on Four planting rows 5 m long with row spacing of 75 cm and density of 9 plants per square meter. The first and fourth rows of male corn and the second and third rows of female corn were planted. The required Nitrogen for the plants was provided from the source of urea fertilizer (500 $kg.ha^{-1}$) in three equal parts before flowering. In order to supply phosphorus, 150 kg of diamonium phosphate per hectare was used before planting. Regarding potash, before planting, 100 $kg.ha^{-1}$ of potassium sulfate was uniformly applied below the planting lines as strips. During the growing season of maize, weeding in the plots was done by hand. The plots were then irrigated in the form of ridge furrow. The level of used water was measured by a meter installed in the field, which was 9000 cubic meters per hectare. The maternal base ears were covered with envelopes immediately after emergence to protect external pollen. Since acceptance of male gametophyte of the mentioned ears, coincided with the beginning of pollination of the male flowers in the paternal rows, envelopes were placed on the male flowers overnight to collect the pollen. The envelope containing the pollen was then placed on the ear in the middle rows for fertilization. Next, pollen collection was repeated for three nights to ensure complete grain closure in rows (to prevent bareness). Finally, in order to conserve the ears, the envelope remained until the end of pollination period. The seeds were harvested when the ears reached the desired moisture content. Moreover, in order to measure seed moisture content, moisture content was frequently determined by a digital hygrometer [4]. The seeds were then separated from the ears to determine both their germination characteristics in different seed tests.

2.3 Measuring Traits

After physiological maturity stage and removing two rows of the margins in each plot, an area equivalent to three square meters was harvested to determine grain yield. Finally, grain yield was reported with initial moisture content at harvest time and 14% moisture content.

The Germine software was used to calculate the maximum germination, germination rate, and germination uniformity [21]. Using this software, the time to onset of 50% germination (H_{50}) was calculated through linear interpolation method in cumulative germination curve.

Germination rate (R_{50}) was also evaluated inversely to the time of reaching 50% of the maximum germination percentage by Eq. 1.

$$\text{Germination rate } R_{50} = 1.{H_{50}}^{-1} \tag{1}$$

In this study, germination uniformity (GU) is refered to the time during which germination incresaes from 10% maximum (H10) to 90% maximum (H_{90}), which was calculated by Eq. 2 [21].

$$\text{Germination uniformity GU} = D_{90} - D_{10} \tag{2}$$

Germination index (GI), or in other words, the mean germination time was further determined by Eq. 3.

$$\text{GI} = \Sigma\text{di ni}.\ \Sigma\text{ni}^{-1} \tag{3}$$

Also, germination properties H_5 (time to 5% germination), H_{10} (time to 10% germination), H_{50} (time to 50% germination time), H_{90} (time to 90% germination), and H_{95} (time to 95% germination) were determined according to Guasnr model [21]. In addition, germination description process was performed based on this model.

2.4 The Simulated Tests of Some Stresses

The experiments were conducted on seed vigor and germination of hybrid maize under simulated tests of some stresses. These simulated tests were in the form of cold, Hiltner brick gravel tests and the standard germination (control) on seed vigor and drought stress test (with polyethylene glycol) on seed germination of hybrid maize.

2.5 Standard Germination Test

First, after disinfection with 5% sodium hypochlorite solution for 30 s, the seeds were washed with distilled water. They were then placed in a 12 cm sterile disposable petri dish. Whatman No. 1 filter papers were placed in each petri dish and 5 ml of distilled water was poured into each petri dish. Next, the petri dishes were placed inside an incubator at the controlled temperature of 25 ± 1 °C. Five days after the start of the experiment; 5 ml of distilled water was added to the petri dishes again. The germinated seeds were counted every 24 h. In the end, the duration of standard germination test was estimated to be 6 days according to ISTA rules [5].

2.6 Cold Test

In order to perform cold test, the seeds were incubated for 5 days at 5 °C and another 7 days at 25 °C. At the end of the test, germination indices and seed vigor were evaluated according to standard germination test [21].

2.7 Hiltner Brick Gravel Test

To perform this test, 250 ml of distilled water was added to 1100 g of sterilized brick gravel and the resulting mixture was allowed to stand for one hour. Then, a 3 cm thick layer of wet crushed brick was put at the bottom of the plastic box and 100 seeds of maize were planted into crushed brick layer without any contacts with each other to avoid infection. A 3–4 cm thick layer of wet brick gravel was also laid on them and the box was kept in the dark at 25 °C for 14 days in an incubator. Finally, evaluation of germination indices and seed vigor was made according to standard germination test [21].

2.8 Drought Stress Test

In order to perform this test, the seeds were subjected to the standard germination test, with the difference that instead of distilled water, solution of 6000 polyethylene glycol in concentrations of -1 MPa was used (According to Eq. 4) [22]. Finally, evaluation of germination indices and seed vigor was made according to standard germination test.

$$\Psi_S = -(1.18 \times 10^{-2})\,C - (1.18 \times 10^{-4})C^2 + (2.67 \times 10^{-4})\,CT + (8.39 \times 10 - 7)C^2T \quad (4)$$

Where Ψ_S is Osmotic potential of PEG-6000, C is the concentration of PEG-6000 in g/kg H,O and T is the temperature in °C.

2.9 The Comparison of Means

The comparison for different tests was conducted using excel 2016 software. Means of different treatment were compared using standard error.

3 Results

3.1 Cumulative Germination

The process of cumulative germination of maize in response to moisture content treatments at maturity time and silicon foliar spraying with the resistances it creates in the plant showed different patterns in standard germination test. Similarities and differences between germination responses to different moisture contents at maturity time are evident (Fig. 1). The nonlinear model (in the germination response curve) showed a relatively similar trend in all moisture treatments at maturity, so that it followed Guasnr model. According to the results reported in Fig. 1 and 30% moisture content at maturity time shows better germination parameters.

With silicon foliar spraying, the shortest time until the beginning of 5, 10, and 95% of germination was observed in 30% moisture content treatment at maturity time, although it showed no difference with 35 and 40% moisture content at maturity time. Also, silicon application, the time it took until the beginning of 5 and 10% of germination showed no difference between moisture content treatments at maturity time. However, 30% moisture content treatment at maturity time was able to improve germination rate to some extent compared to other treatments. Therefore, in standard germination test, moisture contents at maturity time had different effects on germination indicators.

Based on Guasnr model, fitness of the nonlinear model of the germination response curve for the percentage of moisture content at maturity time for drought stress test of 1 MPa was similar to other tests (Fig. 2). According to Fig. 2 and 30% moisture content treatment at maturity time showed the highest germination percentage and rate. However, a reduction in the slope of germination response curve relative to moisture content treatments at maturity time was observed for drought stress test, especially at 1 MPa. However, treatments with 40 and 45% moisture content at maturity time reduced germination process.

The shortest time until the onset of 5, 10, 50 and 95% germination was obtained from drought stress tests of 1 MPa in 30% moisture content treatment at maturity time (Fig. 2). Also, similar to other tests in this study, early harvest of seeds with high moisture content at maturity time delayed germination. However, the treatment with 30% moisture content at maturity time was able to improve germination rate to some extent compared to other treatments. Therefore, we can claim that moisture content treatments at maturity time have different effects on germination indicators in drought stress test.

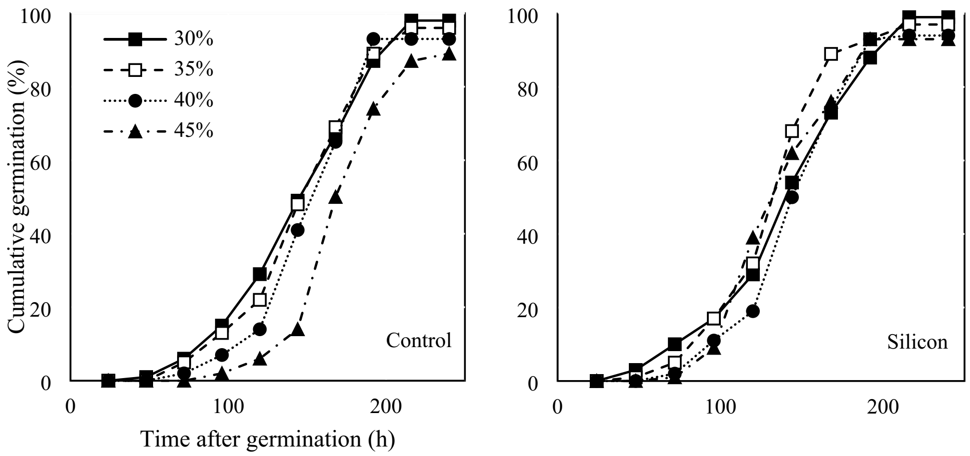

Fig. 1 Germination percentage of corn seeds in different moisture harvests with silicon foliar application under standard germination test conditions

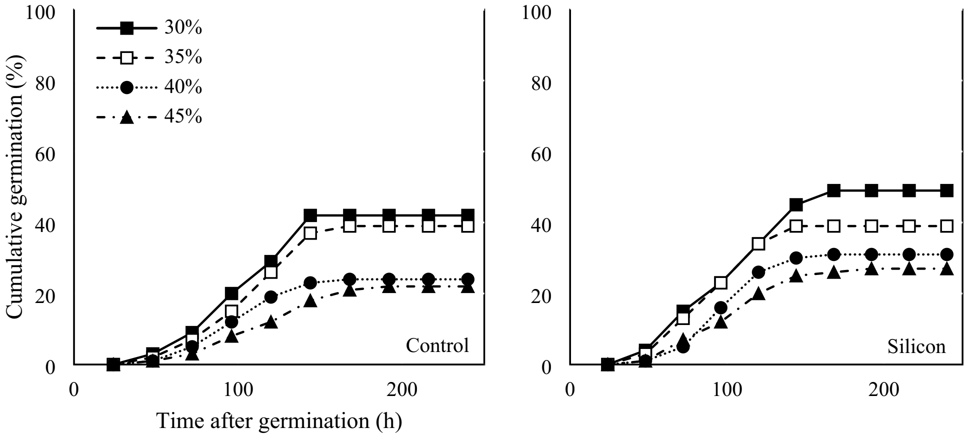

Fig. 2 Germination percentage of corn seeds in different moisture harvests with silicon foliar application under drought stress test (–1 Mpa) conditions

According to Guasnr model, the nonlinear model of the germination response curve was also fitting to moisture content treatments at maturity time for the brick gravel test (Fig. 3). Tables 1 and 2 show that 30% moisture content treatment at maturity time has led to an acceptable germination percentage and rate. Also, the reduction in the slope of germination response curve to moisture content treatments at maturity time was significant for brick gravel test, especially with silicon application (Fig. 3).

Moreover, in this investigation, the shortest time until the onset of different germination percentages with silicon foliar spraying was observed with 30% moisture content treatment at maturity time. Also, the time it took until germination in 30% moisture content treatment at maturity time showed no difference with 35% moisture content treatment at maturity time. On the other hand, 45% moisture content treatment at maturity time caused a delay in germination time for different percentages.

Similar to standard germination test, the process of cumulative germination in response to different moisture content treatments at maturity time showed different patterns in cold test (Fig. 4). However, following Guasnr model, the nonlinear model of germination response curve displayed relatively similar trends for different moisture content treatments at maturity time for the cold test. Furthermore, according to the reported results in Fig. 4 and 30% moisture content treatment at maturity time showed higher germination percentage and rate.

Additionally, with silicon foliar spraying, the shortest time until the beginning of maize germination at different times was observed in 30% moisture content treatment at maturity time. However, 40% moisture content treatment at maturity time delayed germination of maize seeds in the cold test. Also, the time until the onset of maize germination in 30 and 35% moisture content treatments at maturity time showed no difference.

3.2 Germination Max

The results showed that the increase in moisture content at the time of maturity resulted in the decrease of germination percentage in the standard, drought stress, brick gravel, and

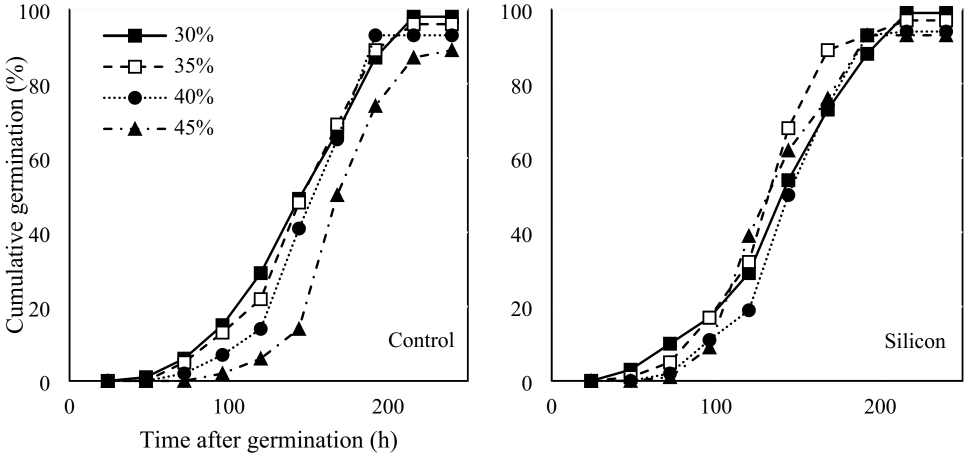

Fig. 3 Germination percentage of corn seeds in different moisture harvests with silicon foliar application under brick gravel (Hiltner) test conditions

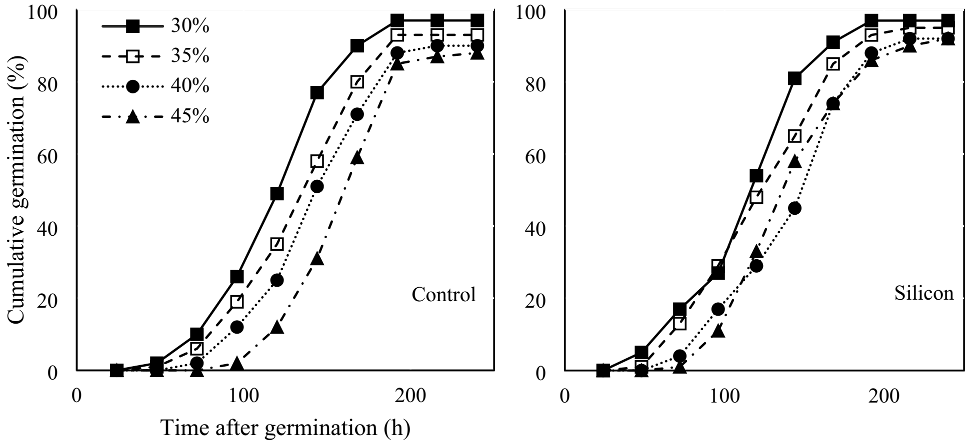

Fig. 4 Germination percentage of corn seeds in different moisture harvests with silicon foliar application under cold test conditions

cold germination tests (Table 1). Therefore, the highest germination percentage was obtained from the 30% moisture content at maturity time in the amount of 99% in silicon application. But, the treatment with 45% moisture content caused the decline in the germination of maize in different germination tests without the use of silicon (Table 1). Moreover, the treatment of 45% moisture content at maturity time without silicon application compared to the treatment with 30% moisture content, reduced the germination percentage at maturity time for standard germination test (5%), drought stress test (48%), brick gravel test (20%), and cold test (8%). With silicon application, a similar germination process was discovered in comparison to without the use of silicon. So, the decline in the germination of the early seed harvest was obtained by drought stress and brick gravel tests. However, the germination response to seed moisture at harvesting time for the cold test was more in line with the standard germination test.

3.3 Germination Rate

The increase in moisture content at the time of maturity reduced germination rate for drought stress, brick gravel and cold tests. So that the maximum germination rate was obtained in 30% seed moisture at harvesting time in the amount of 0.037 germination per hour. However, the treatment with 45% moisture content at maturity time decreased the germination rate of maize for various tests (Table 2).

Table 1 Comparison of Germination Max (%) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	98.33±1.53	99.33±0.49	42.00±13.09	48.67±8.02	76.67±4.77	78.67±2.31	95.67±2.89	96.67±2.89
35	96.00±1.15	97.33±0.00	33.33±13.74	45.33±1.31	74.00±4.29	76.00±4.29	93.33±2.89	95.00±0.00
40	93.33±2.81	94.00±2.58	24.00±5.93	30.67±1.15	64.00±4.03	67.33±4.29	90.00±0.00	91.67±2.89
45	93.33±5.07	93.33±2.74	20.67±6.21	28.67±1.15	59.33±4.29	62.67±6.02	88.33±2.89	91.67±6.64

Data were expressed as mean ±SE (Standard Error)

Table 2 Comparison of Germination Rate (per hour) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	0.007±0.001	0.007±0.001	0.010±0.036	0.010±0.002	0.001±0.002	0.009±0.008	0.009±0.001	0.009±0.000
35	0.007±0.001	0.008±0.000	0.010±0.0006	0.011±0.001	0.001±0.002	0.009±0.008	0.008±0.001	0.008±0.001
40	0.006±0.001	0.007±0.000	0.010±0.0005	0.011±0.002	0.0006±0.000	0.007±0.007	0.007±0.000	0.007±0.000
45	0.006±0.000	0.008±0.001	0.008±0.002	0.012±0.003	0.0006±0.000	0.007±0.007	0.006±0.000	0.007±0.000

Data were expressed as mean ±SE (Standard Error)

Likewise, the germination rate of maize seeds in the treatment with 30% moisture content at maturity time displayed more similarity to the treatment with 35% moisture content for different tests with silicon application. Thus, the decrease of germination process in early seed harvest was obtained with different tests compared to the standard germination test.

3.4 Germination Uniformity

The decrease in germination uniformity was observed in standard, drought stress, brick gravel, and cold germination tests with increasing seed moisture at harvesting time (Table 3). So that the maximum germination uniformity was detected in the treatment with 30% moisture content at maturity time. However, early harvest treatment with 45% moisture content resulted in the decrease of maize germination uniformity for different tests with silicon application (Table 3). The treatment with 45% moisture content at maturity time compared to the treatment with 30% moisture content resulted in the decrease of germination uniformity with silicon foliar spraying for standard test (26% and 31%) and drought stress test (3% and 21%). Also, the decrease of germination uniformity was detected without silicon application for brick gravel test (17% and 24%) and cold test (17% and 15%). Nevertheless, the early harvest with 45% seed moisture has different effects on germination uniformity in different tests.

3.5 Germination Index

Different moisture content treatments at maturity time led to changes in Germination Index (GI), or in other words, the mean germination time with silicon foliar spraying (Table 4). So that the increase in germination index for the standard, drought stress, brick gravel, and cold tests was observed with an increase in seed moisture at harvesting time (Table 4). The minimum average germination time was detected in the treatment with 30% moisture content at maturity time. However, early harvest treatment with 45% moisture content increased average germination time of maize for various tests without silicon foliar spraying (Table 4). Nevertheless, different tests compared to the standard germination test displayed approximately identical effects on the germination index or in other words, the average germination time.

3.6 Catalase

The results indicated that the early harvest coinciding with higher moisture content at maturity time, resulted in an increase in the activity of the Catalase antioxidant enzyme in standard, drought stress, brick gravel, and cold tests (Table 5). So that the maximum activity of the Catalase antioxidant enzyme was obtained in the treatment with 35% seed moisture at harvesting time for various tests with silicon

Table 3 Comparison of Germination Uniformity (hour) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	96.36±16.03	114.29±29.81	81.02±11.61	91.24±8.21	84.21±24.11	89.90±14.82	87.41±6.59	93.60±19.90
35	87.97±25.36	92.59±30.50	77.79±4.43	82.42±9.36	79.45±5.14	86.45±9.15	91.17±18.09	102.11±4.69
40	78.01±13.58	81.31±17.43	53.21±19.88	72.24±10.09	71.88±2.97	79.59±24.67	89.58±17.84	98.29±4.05
45	70.75±9.87	78.22±8.41	68.95±6.98	81.22±19.55	64.19±23.69	74.80±14.28	72.65±11.16	79.87±26.38

Data were expressed as mean ±SE (Standard Error)

Table 4 Comparison of Germination Index of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	6.39±0.83	6.29±0.53	4.51±0.21	4.50±0.66	5.24±0.74	4.99±0.46	5.36±0.59	5.16±0.44
35	6.46±0.50	5.82±0.03	4.79±0.18	4.19±0.21	5.28±0.86	5.33±0.45	5.87±0.47	5.49±0.59
40	6.62±0.20	6.36±0.20	4.53±0.12	3.69±0.62	6.28±0.08	5.75±0.28	6.24±0.27	6.19±0.28
45	7.37±0.07	6.02±0.46	5.28±0.69	4.71±1.05	6.77±0.32	5.55±0.15	6.88±0.28	6.12±0.47

Data were expressed as mean ±SE (Standard Error)

Table 5 Comparison of Catalase (µmolmin− 1 mg protein) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	28.73±0.41	30.14±0.43	33.77±1.11	35.13±0.51	29.30±0.42	30.68±0.42	29.80±0.50	32.11±0.24
35	29.69±0.58	31.18±0.72	34.25±0.56	36.60±0.47	30.31±0.56	32.80±0.33	32.71±0.40	34.30±0.12
40	27.79±0.41	29.26±0.63	30.15±0.47	32.62±0.58	27.96±0.26	29.58±0.46	27.68±0.37	30.10±0.56
45	26.19±0.62	28.63±0.40	28.45±0.90	30.18±0.45	27.54±0.41	29.17±0.48	27.24±0.49	29.53±0.48

Data were expressed as mean ±SE (Standard Error)

foliar spraying (Table 5). The treatment with 35% moisture content at maturity time with silicon use compared to the treatment with 30% moisture content resulted in an increase in the activity of the Catalase antioxidant enzyme for standard test (7% and 8%) and drought stress test (23% and 20%). Also, the increase in the activity of the Catalase antioxidant enzyme was detected for brick gravel test (13% and 12%) and cold test (15% and 16%) with silicon application. As a result, the maximum activity of the Catalase antioxidant enzyme in early seed harvest was obtained in the treatment with 35% seed moisture using brick gravel test. Also, at a lower level, the activity of the Catalase antioxidant enzyme was detected in the brick gravel and the cold tests.

3.7 Ascorbat Peroxidase

The early harvest of the maize seeds resulted in an increase in the activity of Ascorbate Peroxidase antioxidant enzyme similar to the activity of the Catalase enzyme antioxidant in standard, drought stress, brick gravel, and cold tests (Table 6). So that the maximum activity of the Ascorbate Peroxidase antioxidant enzyme was detected in the treatment with 35% moisture content for various tests with silicon application (Table 6). The treatment with 35% moisture content at maturity compared to the treatment with 30% moisture content resulted in an increase in the activity of the Ascorbate Peroxidase antioxidant enzyme for standard test (1% and 1%) and drought stress test (6% and 6%) with silicon application. Also, the increase in the activity of the Ascorbate Peroxidase antioxidant enzyme was detected for brick gravel test (5% and 5%) and cold test (5% and 5%) with silicon application. As a result, the maximum activity of the Ascorbate Peroxidase antioxidant enzyme in early seed harvest was obtained in the treatment with 35% seed moisture using brick gravel test.

3.8 Malone Dialdehide

The delayed harvest of the maize seeds, or in other terms, 45% moisture content of the seed at the time of harvest, illustrated lower amount of Malone Dialdehyde (Table 7). On the other hand, early harvest at 45% moisture content of the seed resulted in an increase in the amount of Malone Dialdehyde for various tests with silicon application (Table 7). So that 35% seed moisture at harvesting time led to an increase in the amount of Malone Dialdehyde for standard test (2% and 2%) and drought stress test (24% and 25%) with silicon application. Also, the increase in the amount of Malone Dialdehyde was obtained for brick gravel test (20% and 20%) and cold test (22% and 22%) with silicon application. As a result, the maximum amount of Malone Dialdehyde in early harvest of maize seeds was detected in 35% moisture content using brick gravel test. Also, at a lower level, the increase in the amount of Malone Dialdehyde was detected in the brick gravel and the cold tests compared to the standard test.

Table 6 Comparison of Ascorbat Peroxidase (nmolmin− 1 mg) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	2554±5	2654±6	2663±15	2769±12	2630±16	2748±22	2650±18	2762±33
35	2573±18	2681±21	2716±17	2829±19	2680±19	2784±21	2698±16	2806±24
40	2547±12	2655±13	2621±13	2724±9	2580±15	2694±10	2601±19	2713±22
45	2543±14	2645±17	2563±16	2671±14	2554±21	2659±18	2556±18	2667±24

Data were expressed as mean ±SE (Standard Error)

Table 7 Comparison of Malone Dialdehide (nmol.mgFW− 1) of maize seeds at harvest times on based of seed moisture content under simulated environmental stresses with silicon foliar application

Seed Moisture Content (%)	Standard germination		Drought stress		Brick gravel		Cold	
	Control	Silicon	Control	Silicon	Control	Silicon	Control	Silicon
30	1829±13	1870±14	2181±24	2244±22	2121±25	2174±25	2200±11	2241±17
35	1852±15	1912±14	2347±20	2376±28	2202±21	2251±19	2286±26	2312±15
40	1811±14	1863±8	2058±16	2115±25	1900±8	1945±7	1996±27	2022±19
45	1805±10	1861±11	1902±15	1904±28	1851±27	1873±17	1821±20	1893±23

Data were expressed as mean ±SE (Standard Error)

4 Discussion

In this study, the effect of moisture content and silicon application on maize grain germination indicators, and seed quality were evaluated. The stress factors were introduced using low temperature germination, brick gravel and drought stress test. These findings are explained and compared in context of current research.

The germination rate and percentage of maize was strongly influenced by moisture content and silicon application. The harvested seeds with 30% moisture had the least pre-harvest aging and thus had the highest germination. In general, germination does not occur until the seed has completed the minimum morphogenic stages required for embryonic development [23]. The larger and more mature the seed is the more the greater the seed vigor. Therefore, increasing germination percentage can be expected with reduced seed moisture content at harvest time [24]. The germination percentage in the low temperature germination test showed a slight change compared with the standard test, and the seed germination rate was somewhat higher. This correlates with other reports that have found that cold pretreatments change indicators related to seed germination and vigor by activating the seed's physiological mechanisms [25]. Therefore, cold pretreatment could accelerate germination process by stimulating the germination process [25].

Germination indicators were expected to decline during this test as aging affects the activity of hydrolyzing enzymes and other cellular systems that transfer seed stock material [26]. In addition, reports attribute reduced seed vigor from seed tests to the complete degradation of the cytoplasmic membrane structure of seed cells [27]. Our finding revealed that seed tests reduce vigor of maize seeds particularly with high moisture content from improper harvest time.

There have been many reports on reduced germination and related indicators in seeds affected by drought stress test with polyethylene glycol solution and mechanical stress with the brick test [28, 29]. Both treatments led to a decrease in the slope of germination response curve to moisture content treatments at harvest time. Some researchers have attributed the germination response to drought stress due to the movement and transfer of seed stock as polyethylene glycol reduces hydrolysis of seed stock material [30]. Our findings indicated that the highest germination percentage and rate occurred with drought stress conditions of 1 MPa and 30% moisture content at harvest time. Results of the brick test clearly confirmed the reduction in germination indicators with inappropriate maturity moisture content. The high correlation of the brick test results has also been reported with field results for seed germination [31, 32].

In summary, the findings of this research confirm well the previous studies and add to the investigation of the effect of seed moisture and silicon application on seed quality. It was found seed quality was best with 30–35% seed moisture. On the other hand, treatments with 40 and 45% moisture content at harvest time significantly reduced germination process.

The seed deterioration process may be due to the denaturation of biomolecules, production and accumulation of toxic substances, and destruction of cell membrane structure [33].

The reports show that the increase in the amount of Malone Dialdehyde during the deterioration process is due to the hydrolysis of storage materials during the germination process [34]. Thus, it can be assumed that this confirms the findings of this study in terms of the increase in the negative effects of early harvest of maize seeds at a moisture content of 45%. On the other hand, the increase in the activity of the Catalase and Ascorbate Peroxidase antioxidant enzymes during environmental stresses; including drought stress, brick gravel, and cold tests is a kind of defense mechanism for plants. This mechanism mainly happens due to the disruption of cytoplasmic membrane structure of the seed cells. Catalase is an enzyme that detoxifies hydrogen peroxide by converting it into water and eventually to oxygen [35]. Moreover, the Ascorbate Peroxidase enzyme decreases the amount of hydrogen peroxide [36]. The increase in the capacity of the antioxidant enzymes is a general response to cell membrane destruction due to the seed deterioration [37]. Thus, it appears that the increase in the activity of antioxidant enzymes has been in response to the detrimental impacts of the oxygen produced by the deterioration of the maize seeds.

5 Conclusion

Results of this study showed that seed germination quality was influenced by the combined effect of harvest moisture content and silicon use. In particular, the slope of the germination response curve to moisture content at maturity time was observed for the brick gravel, and drought stress tests. The obtained results also indicated that seed moisture during harvest time and silicon foliar spraying may have a role in seed vigor reduction by affecting seed aging process. Maize seed quality was best with 30–35% moisture content and with silicon foliar spraying. On the other hand, treatments with 40 and 45% moisture content at harvest time significantly reduced germination process.

The moisture content of 35% at maturity time and silicon use led to an increase in an increase in the activity of Catalase and Ascorbate peroxidase antioxidant enzymes, especially in drought stress test. In other moistures, the activity of Catalase and Ascorbate peroxidase antioxidant enzymes was detected in the brick gravel and the cold tests. The increase in the amount of Malone Dialdehyde of the maize at 45% moisture content compared to 30% moisture content affirms this claim. Nevertheless, early seed harvest resulted in the increased negative effects of drought stress, brick gravel, and cold tests on the seeds compared to the standard germination test.

At the end of the experiment, it is suggested to evaluate seed priming with silicon and compare it with foliar application and the effect of growth stimulants such as Mycorrhizal fungi or Pseudomonas bacteria under simulated environmental stresses and compare with silicon foliar spraying.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Consent to Participate No Human Participants and/or Animals were involved in this research.

Consent for Publication The authors hereby provide consent for the publication of the manuscript.

Competing Interests The authors declare no competing interests.

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