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Vegetable-Seed Storage as Affected by Temperature and Relative Humidity¹

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INTRODUCTION

The rate of deterioration of some vegetable seeds when stored at high temperatures and high humidities comparable to those prevailing in Gulf States has been determined (4).² The present study of vegetable-seed storage was designed as an extension of that work to provide intermediate conditions of temperature and humidity, to extend the period of storage, to include additional kinds of seeds, and to retest some kinds of seeds from another seed crop.

Since the publication of Technical Bulletin 708 (4) a paper by Barton (3) on the relation of temperature and humidity to viability of seeds and one by Rodrigo and Tecson (8) on the relation of seed moisture to vegetable-seed storage have appeared. Akamine (1) has reported the effect of temperature and humidity on storage of vegetable and farm-crop seeds.

¹ Submitted for publication April 28, 1948.

² Italic numbers in parentheses refer to Literature Cited, p. 24.

MATERIALS AND METHODS

SEEDS

Seeds of 15 vegetables of the preceding season's crop (1939) were obtained from reliable producers as soon as feasible after they had been cleaned. Upon receipt of the seeds at Beltsville, Md., they were stored at about 40° F. and a relative humidity of 50 percent for 4 to 6 weeks until put under the various experimental storage conditions on February 12, 1940.

The kinds and varieties of seeds tested included snap bean (Bountiful); cabbage (All Seasons); carrot (Red Core Chantenay); celery (Golden Supreme); sweet corn (Clarks Early Evergreen); cucumber (Early Fortune); lettuce (Imperial 44); okra (Perkins Mammoth); onion (Yellow Bermuda); pea (Laxton Progress); pepper (Oakview Wonder); spinach (Long Standing Bloomsdale); tomato (Rutgers); turnip (Purple Top White Globe); and watermelon (Klondike R 7).

STORAGE CHAMBERS

Eight controlled storage conditions were provided in closed sheet-iron chambers or compartments, approximately 3 by 2½ by 3½ feet. The chambers were placed in rooms that were kept at the three temperatures (50°, 70°, and 80° F.) desired for the experiment by means of brine-refrigeration coils, circulating fans, and heaters. The humidity of these temperature-controlled rooms in which the chambers were placed was approximately 50 percent. For the control of humidity, each compartment was equipped with a fan, a water surface, and a humidistat with hair elements which controlled a relay device that operated two doors, each of about 4 square inches, in the side wall of the compartment near the fan. These doors allowed the introduction of low-humidity air from the storage room into the compartment and provided a quick control of humidity within the chamber by combining the air of the two humidities. The humidities that were intended to be maintained were 50 and 80 percent at 50° and 65, 73, and 80 percent at both 70° and 80°. Daily readings were made of the dry- and wet-bulb thermometers as a check on the control and as a record of the conditions that were actually maintained.

In order to approximate warehouse storage, an additional chamber of similar size but enclosed with wire screens to exclude rodents and insects was placed in a small, unheated frame building at Beltsville, Md. Temperature and humidity were recorded by a hygrothermograph.

DISPOSITION OF SEED

After the original moisture and germination tests, each kind of seed was divided into 108 small portions of sufficient size for additional moisture and germination tests. Each portion was placed in a small, open ointment box fixed to wooden strips to facilitate handling. The boxes were uniformly spaced so that each strip held 1 sampling of each of the 15 kinds of seeds. The strips with the open boxes of seed were placed in each chamber so that all seeds had easy access to freely circulating air.

SEALED STORAGE

In the comparison of sealed and open storage, the seeds for both kinds of storage were exposed in the humidity chambers for 6 weeks. Then the samples for sealed storage were removed and quickly placed in glass vials with screw caps sealed with hot paraffin. The sealed vials were returned to the respective chambers. At certain of the regular sampling periods some of the sealed samples were removed and moisture and germination tests were made on them at the same time as on open-storage samples from the same chambers. This was done at times when a moderate to severe loss of viability could be expected.

SAMPLING

After the original moisture and germination samples had been drawn, the seed was placed at the different storage conditions on February 12, 1940. Samples were taken at 3-week intervals for 36 weeks. Upon removal from the storage chamber, each sample was mixed and a small portion was quickly placed in a glass-stoppered weighing bottle for moisture determination; the remainder was placed in a paper envelope for a prompt germination test. For moisture determination about 10 gm. of seed was used for bean, pea, corn, and okra, about 5 gm. for watermelon and cucumber, and 2 gm. for the small seeds. The seed was dried in a large forced-circulation electric drying oven at $100^{\circ} \pm 0.5^{\circ}$ C.; the large seeds were dried 48 hours and the smaller ones 24 hours.

GERMINATION TESTS

The portions of seed placed in paper envelopes upon removal from the several chambers were held at a temperature of about 50° F. until they could be tested for germination. All germination tests were started within 2 days after the sample was taken. Any unused portions of these samples were held in cold storage until about 1 year after the beginning of the experiment, when all samples of a given kind of seed were retested for germination on the same day.

Germination tests were conducted in accordance with the recommendations of the Association of Official Seed Analysts of North America (2), with the exception of those for celery, bean, and corn. Preliminary tests of celery had shown that this sample germinated better at a daily temperature alternation of 15° to 25° C. than at one of 20° to 30° . The celery seed was germinated at these 2 temperature alternations, but only the results obtained at the former alternation are presented here. Bean and corn seeds were germinated in flats of sterilized soil in a greenhouse. Quadruplicate 100-seed tests were used except for okra, for which 8 tests of 100 seeds each were used for each sample.

STORAGE CONDITIONS MAINTAINED

With the equipment available it was not feasible to control temperature or humidity within very narrow limits, but the different levels were maintained sufficiently for the purposes of the experiment.

Weekly means of temperatures and humidities are shown in figure 1; and means for the entire period of the experiment with standard errors, based on the 3-week means between sampling periods, are given in table 1.

The values shown in figure 1 and table 1 are based on daily readings at one point in each chamber and are believed to be accurate for this place in the chamber and for the time of reading. Although a fan was maintained in each chamber, these readings may not represent average conditions surrounding the seeds as closely as is indicated by the values given. This is especially true for humidity. Temperatures of the separate chambers in each room were very nearly alike; therefore, in figure 1, A, the temperatures are given for only one chamber in each room. In general, the temperatures tended to be slightly lower at the higher humidity levels, possibly because of evaporation of larger quantities of water in those chambers.

TABLE 1.—Mean temperatures and humidities and their standard errors, in the various storage chambers

[Each value based on 12 successive 3-week periods]

Intended temperature and humidity of storage chamber	Mean temperature	Mean humidity	Intended temperature and humidity of storage chamber	Mean temperature	Mean humidity
50° F.:	° F.	Percent	80° F.:	° F.	Percent
50 percent.....	52.1±0.46	52.4±0.76	65 percent.....	80.4±.19	65.8±.35
80 percent.....	51.7±.35	80.1±.44	73 percent.....	80.3±.19	73.4±.39
70° F.:			80 percent.....	79.9±.22	79.8±.24
65 percent.....	71.4±.15	64.5±.42	Warehouse.....	60.5±4.04	71.5±1.36
73 percent.....	70.7±.17	73.3±.24			
80 percent.....	70.3±.08	80.5±.25			

EFFECT OF STORAGE CONDITIONS

SEED MOISTURE

Under the conditions of this experiment all the seeds except bean, pea, and corn reached an equilibrium in moisture content for each storage condition by the end of 3 weeks. The mean moisture contents of the 15 kinds of seeds for each of the 9 storage conditions are presented in table 2. Irregular fluctuations in moisture content that were not correlated with the air-humidity data obtained or with the germination behavior were observed at different sampling dates. They probably represent variations in precision of moisture determinations as well as actual variations in seed moisture resulting from humidity changes within the chambers preceding the sampling. The analysis of variance of the air humidity and of the moisture content of the several kinds of seeds for the 3 controlled humidities each at 70° and 80° F. is given in table 3. Within the comparatively narrow range of humidity involved in this experiment, the increase of seed moisture with increase of air humidity is essentially linear.

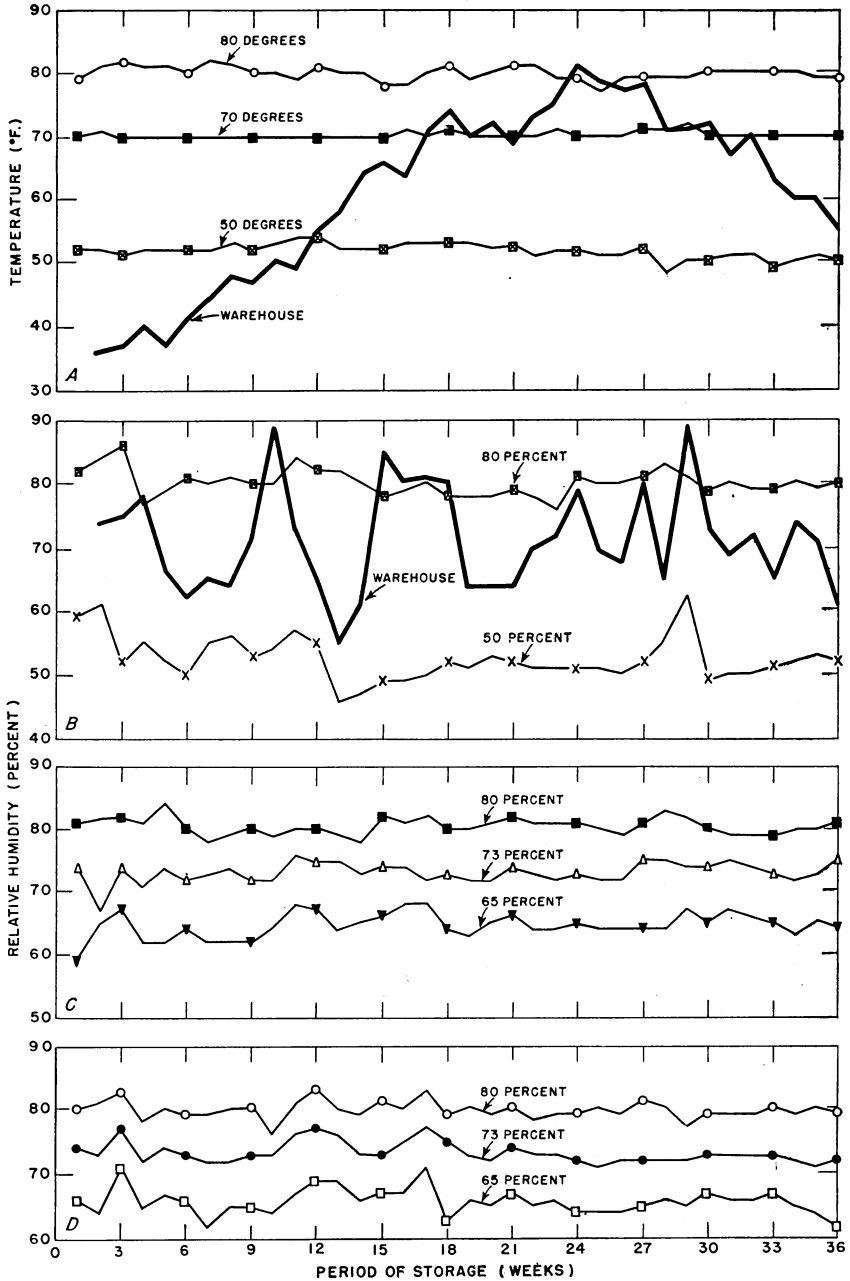


FIGURE 1.—Weekly average temperatures and relative humidities in the storage chambers: A, Temperatures in one chamber (80 percent humidity) in each of the three controlled rooms and in the warehouse; B, relative humidities in the two chambers in the 50° F. room and in the warehouse; C, relative humidities in the three chambers in the 70° room; D, relative humidities in the three chambers in the 80° room.

TABLE 2.—Moisture contents of seeds of 15 kinds of vegetables before and after storage under 9 conditions

[Each value for stored seed based on 12 successive samples taken at 3-week intervals; values for original content based on 2 samples]

Kind of seed	Original moisture content of seed	Mean moisture content of seed stored at indicated mean temperature and humidity									Mean moisture content of seed stored in warehouse, Beltsville
		51.9° F.			70.8° F.			80.2° F.			
		52.4 per-cent	80.1 per-cent	64.5 per-cent	73.3 per-cent	80.5 per-cent	65.8 per-cent	73.4 per-cent	79.8 per-cent		
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	
Bean, snap.....	9.9	10.0	17.4	12.0	14.1	15.1	12.8	14.1	16.3	12.4	
Cabbage.....	8.0	6.6	10.9	7.3	8.5	9.3	7.7	8.6	9.9	8.0	
Carrot.....	9.4	8.2	14.3	9.4	11.2	12.0	10.1	11.0	12.6	10.4	
Celery.....	11.4	9.7	15.4	10.6	12.2	13.2	11.2	12.1	14.0	11.4	
Corn, sweet.....	10.8	10.0	15.2	11.0	12.6	13.3	11.4	12.3	13.7	11.8	
Cucumber.....	8.8	7.7	11.6	8.4	9.4	9.9	8.6	9.3	10.3	9.0	
Lettuce.....	7.6	6.5	10.9	7.4	8.5	9.3	7.8	8.5	9.7	8.1	
Okra.....	11.4	10.4	15.4	11.3	12.7	13.7	11.8	12.8	14.5	12.0	
Onion.....	10.9	9.3	15.1	10.4	11.8	12.8	10.9	11.7	13.2	11.3	
Pea.....	9.8	9.6	16.5	11.3	13.5	14.5	12.1	13.6	15.7	12.1	
Pepper.....	10.0	8.4	13.5	9.2	10.5	11.5	9.5	10.4	11.8	10.0	
Spinach.....	12.4	11.0	16.1	11.9	13.2	14.1	12.2	13.1	14.5	12.7	
Tomato.....	10.0	8.7	13.1	9.6	10.6	11.3	9.8	10.5	11.6	10.3	
Turnip.....	8.2	6.7	10.9	7.4	8.5	9.2	7.8	8.5	9.7	8.0	
Watermelon.....	10.5	8.5	12.6	9.0	10.2	10.9	9.3	10.1	11.3	9.7	

TABLE 3.—Analysis of variance of air humidity and of moisture contents of seeds of 15 kinds of vegetables stored at 3 humidity levels each at 70° and 80° F.

[Humidity readings for 12 successive 3-week periods and moisture contents at the end of each 3-week period]

Source of variation	Degrees of freedom	Variance for humidity	Variance for moisture content of seed of—						
			Bean (snap)	Cabbage	Carrot	Celery	Corn (sweet)	Cucumber	Lettuce
Temperature.....	1	1.17	8.34	2.35	0.93	3.47	0.50	0.47	1.47
Humidity (linear).....	1	2,683.52	134.67	53.13	68.88	87.21	66.03	32.50	44.66
Humidity (quadratic).....	1	7.79	.03	.01	.02	.02	.08	<.01	.09
Temperature X humidity.....	2	5.93	2.23	.46	1.06	1.17	.82	.39	.42
Period of storage.....	11	3.15	1.12	1.45	3.24	2.68	.96	.86	1.42
Error.....	55	.87	.21	.27	.69	.40	.13	.13	.29
Total.....	71								

Source of variation	Degrees of freedom	Variance for moisture content of seed of—							
		Okra	Onion	Pea	Pepper	Spinach	Tomato	Turnip	Watermelon
Temperature.....	1	3.83	1.28	10.27	0.89	0.70	0.24	1.56	0.42
Humidity (linear).....	1	77.01	69.36	143.52	63.02	60.97	39.06	43.70	44.27
Humidity (quadratic).....	1	.05	.07	.34	.03	<.01	.01	<.01	<.01
Temperature X humidity.....	2	.84	.71	1.87	.37	.55	.25	.45	.37
Period of storage.....	11	.71	1.73	1.34	1.33	1.13	1.21	1.32	.75
Error.....	55	.09	.33	.23	.23	.18	.20	.26	.11
Total.....	71								

The results of the analysis of covariance of air humidity (mean for 3 weeks preceding sampling) and moisture content of seed (determined at the end of each 3-week period) for the six controlled conditions at 70° and 80° F. are shown in table 4. The variations in seed

moisture of successive individual determinations did not consistently reflect the small irregular fluctuations in mean air-humidity values for the preceding 3-week period. On the other hand, the correlation was very high between seed moisture and air humidity among chambers for the entire storage period. The correlation within treatments calculated from the variance analysis gave results comparable to those among treatments based on the covariance.

TABLE 4.—*Analysis of covariance of air humidity and of moisture contents of seeds of 15 kinds of vegetables stored at 3 humidity levels each at 70° and 80° F.*

[Humidity readings for 12 successive 3-week periods and moisture contents at the end of each 3-week period; 47 degrees of freedom for each category, based on variance within controlled chambers]

Kind of seed	Correlation between air humidity and seed moisture	Coefficient of regression	Standard error of estimate	Standard error of regression coefficient
	<i>r</i>	<i>b</i>	<i>S_{y.x}</i>	<i>S_b</i>
Bean, snap.....	0.956	0.222	0.517	0.0098
Cabbage.....	.927	.139	.428	.0081
Carrot.....	.868	.160	.699	.0133
Celery.....	.929	.179	.543	.0103
Corn, sweet.....	.956	.155	.362	.0069
Cucumber.....	.935	.109	.315	.0060
Lettuce.....	.906	.127	.453	.0086
Okra.....	.962	.167	.357	.0068
Onion.....	.924	.159	.501	.0095
Pea.....	.957	.229	.529	.0101
Pepper.....	.939	.151	.424	.0081
Spinach.....	.943	.149	.400	.0076
Tomato.....	.920	.119	.386	.0073
Turnip.....	.920	.126	.411	.0078
Watermelon.....	.988	.130	.151	.0028

Examination of table 2 shows that the mean moisture at a given humidity differs greatly among the several kinds of seeds and also that the rate of change in moisture with change in humidity differs considerably. The rates of change are shown in table 4 by the coefficients of regression. Cucumber seed gained only slightly more than 0.1 percent in moisture with each increase of 1 percent in humidity, but bean and pea seeds gained more than twice that amount. The regression values obtained in this study are in close agreement with those found in a previous study by Boswell et al. (4), although the basis of calculation is slightly different.

The present study was not planned to determine the effect of temperature on moisture content of seed, because the recorded mean air humidities may not accurately indicate the true conditions surrounding the seeds. However, examination of table 2 shows that the moisture contents reached by the different kinds of seeds at approximately 80 percent humidity were greater at 51.9° F. than at 70.8° and 80.2°. This tendency for a higher seed-moisture equilibrium at about 50° than at higher temperatures for a given humidity has been noted by Boswell et al. (4) and Barton (3). It is probably due to the lower vapor pressure of the moisture in the seeds at the lower temperature. The slightly but consistently higher seed-moisture values at 80.2° and 79.8 percent humidity than at 70.8° and 80.5 percent humidity cannot be explained, unless the humidity readings in these chambers failed to represent the true humidity surrounding the

seeds. Fenton (6) has pointed out the relation of the vapor pressure of seeds at different temperatures to seed-moisture equilibrium.

The moisture content of seed from warehouse storage varied greatly from period to period because of the widely variable air humidity as shown in figure 1, *B*. However, the predicted mean moisture contents³ for a humidity corresponding to the mean air humidity of the warehouse for the 36 weeks of the experiment were within approximately 0.5 percent of the means of the 12 determined values for all seed kinds, except bean and pea. This indicates the feasibility of predicting with fair accuracy the average moisture content that seed will attain when exposed to air of known mean humidity.

For the individual 3-week periods, it was not possible to predict accurately the moisture content of the warehouse-stored seed. It was found, however, that a closer prediction of seed moisture for the smaller seeds for many of the sampling dates could be made by using a humidity value for the preceding period that gave equal weight to the readings for the 2 days before sampling and for the 2 weeks before instead of the mean for the entire 3-week period. This indicates that, although the moisture of the small seeds exposed as in this experiment changes very rapidly, there is a residual influence of previous humidity conditions. It also indicates that the mean humidity for the 3-week period before sampling (used in calculating the data in table 4) is not the best value for the determination of correlation and coefficient of regression. It would be impractical, however, to determine the best balance of short- and long-time influence of air humidity for each kind of seed as exposed in these particular studies.

In samples of seeds of bean (variety Bountiful) stored for a few weeks under unfavorable conditions, it was observed that the color of the seed coat had darkened. At 80° F. and 80 and 73 percent humidities the natural tan color had changed to a dull reddish brown. There was a slight change of color at 80° and 65 percent humidity. The change at 70° and 80 percent humidity was somewhat less than at 80° and 65 percent humidity. No color change was observed in seeds stored at 50°. It would appear that temperature had more influence than humidity on color change.

SEED VIABILITY

The chief points of interest in the germination results are the time at which viability was first definitely impaired and the rate of decrease in germination thereafter. To present these points most clearly, the germination results for seeds removed from the controlled chambers are shown graphically in figures 2 to 6.

³ Based on the regression coefficient and the mean moisture contents for the six controlled chambers at 70° and 80° F. for each seed kind and on the difference in mean air humidity between the warehouse and the controlled chambers.

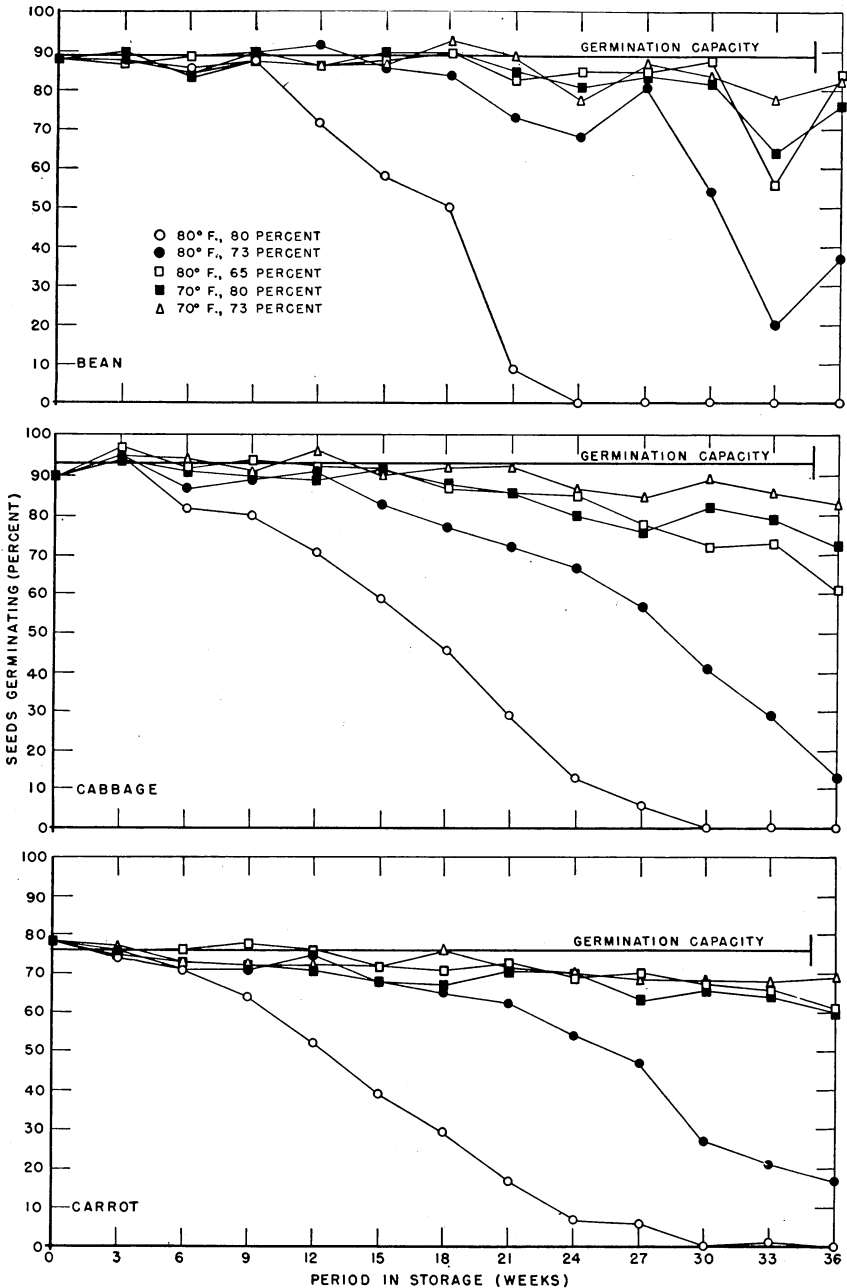


FIGURE 2.—Germination of bean, cabbage, and carrot seeds after storage for 3 to 36 weeks at various temperatures and humidities. Germination capacity (horizontal line) determined from the mean value of tests before storage and of tests from conditions without significant loss of germination within the 36-week period. Amount necessary for a highly significant deviation from each mean: ± 4.0 percent for bean, ± 4.2 percent for cabbage, and ± 4.0 percent for carrot.

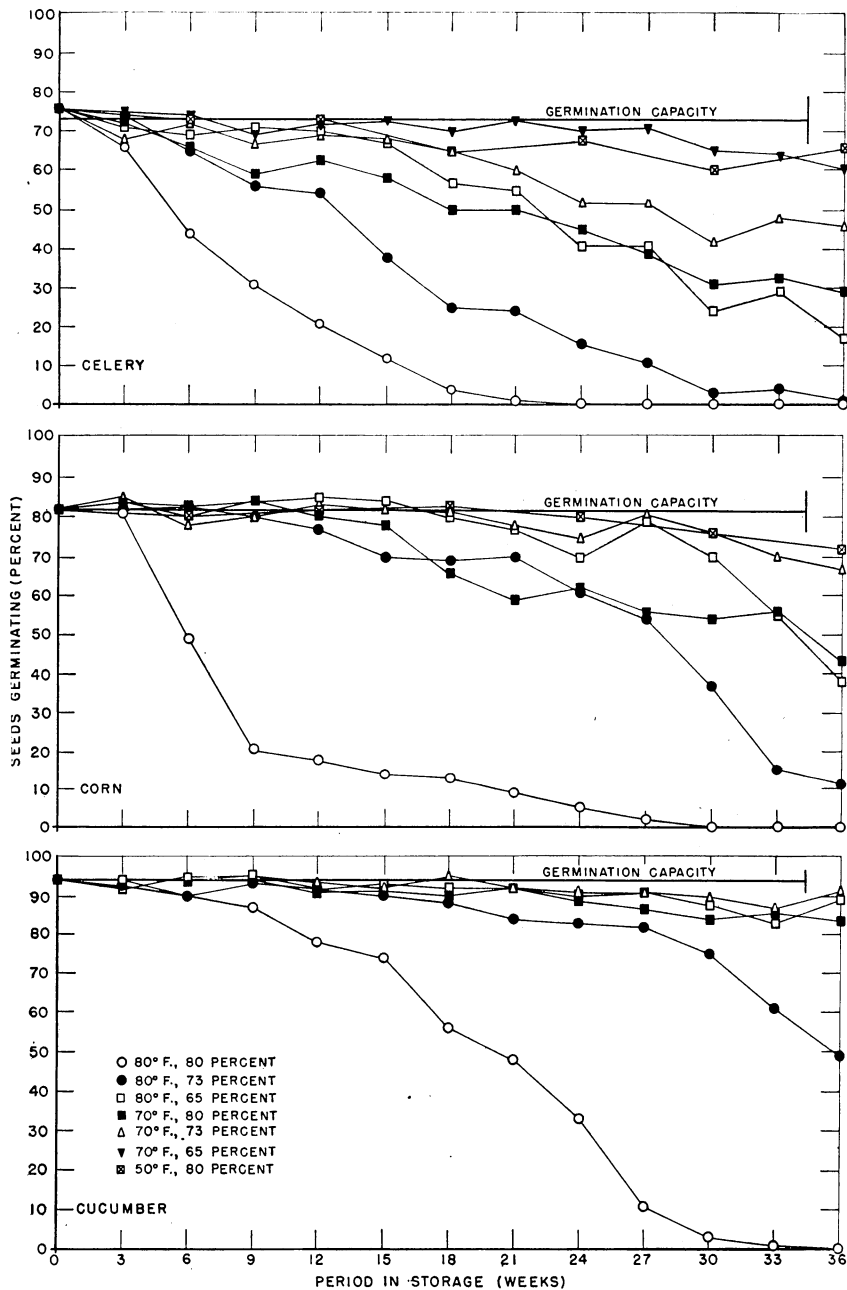


FIGURE 3.—Germination of celery, corn, and cucumber seeds after storage for 3 to 36 weeks at various temperatures and humidities. Germination capacity (horizontal line) determined from the mean value of tests before storage and of tests from conditions without significant loss of germination within the 36-week period. Amount necessary for a highly significant deviation from each mean: ± 6.3 percent for celery, ± 5.2 percent for corn, and ± 3.1 percent for cucumber.

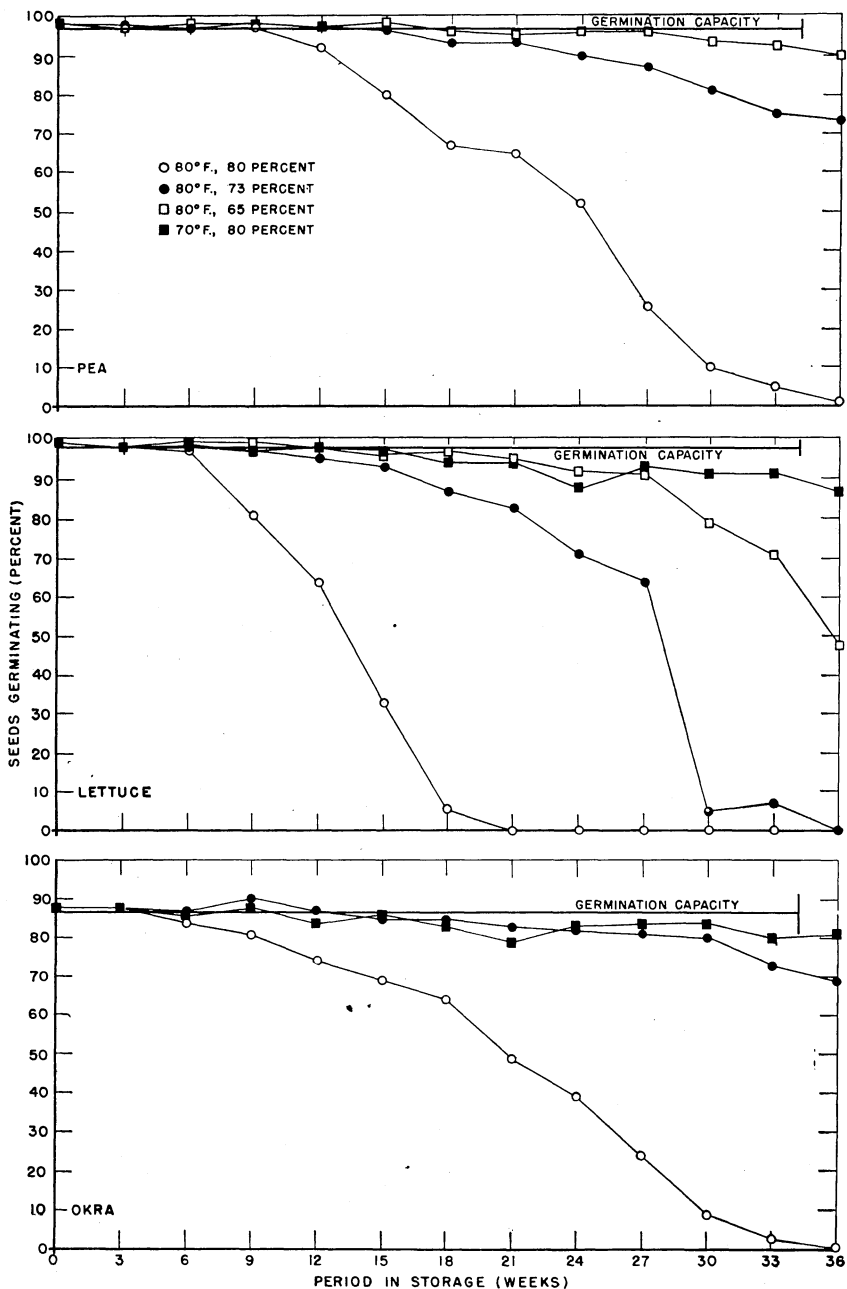


FIGURE 4.—Germination of pea, lettuce, and okra seeds after storage for 3 to 36 weeks at various temperatures and humidities. Germination capacity (horizontal line) determined from the mean value of tests before storage and of tests from conditions without significant loss of germination within the 36-week period. Amount necessary for a highly significant deviation from each mean: ± 2.6 percent for pea, ± 2.1 percent for lettuce, and ± 5.0 percent for okra.

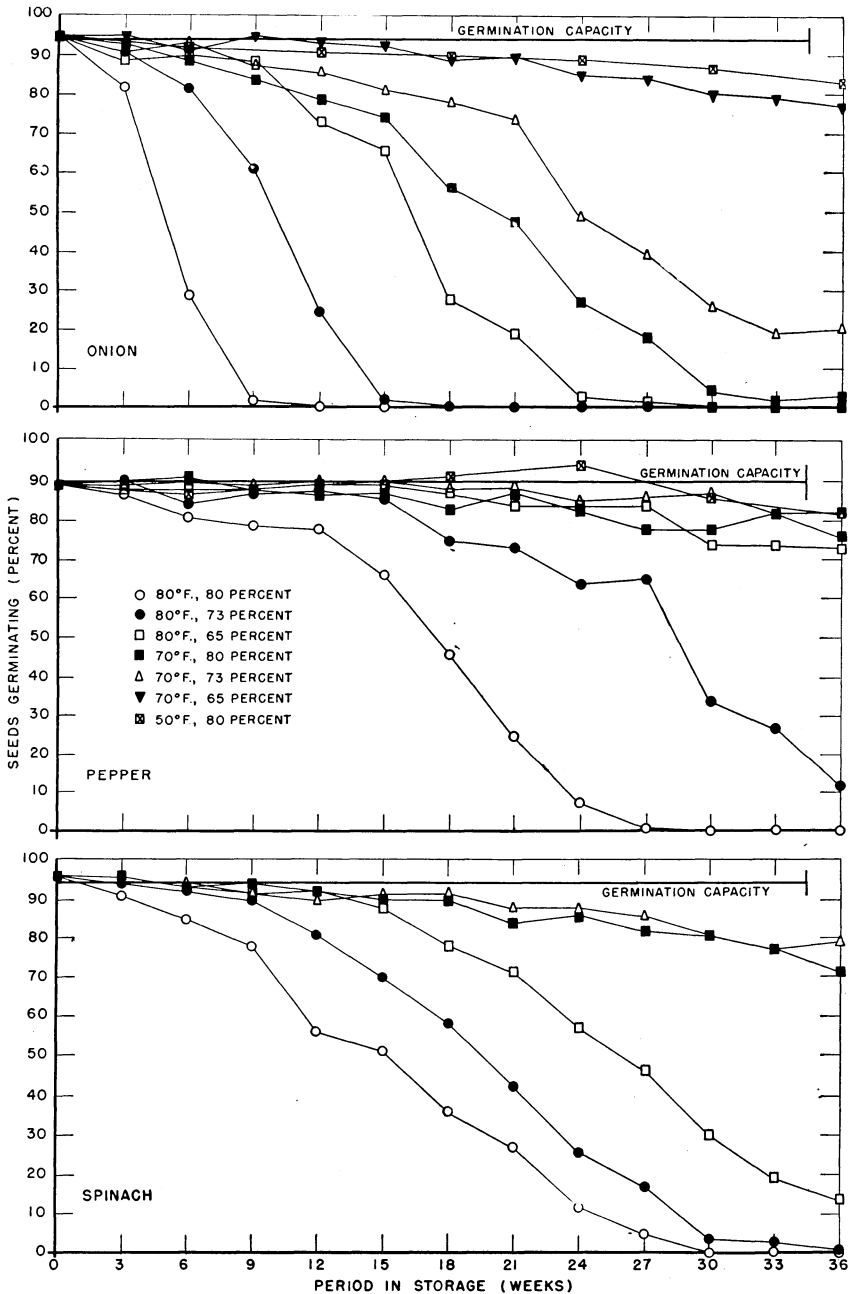


FIGURE 5.—Germination of onion, pepper, and spinach seeds after storage for 3 to 36 weeks at various temperatures and humidities. Germination capacity (horizontal line) determined from the mean value of tests before storage and of tests from conditions without significant loss of germination within the 36-week period. Amount necessary for a highly significant deviation from each mean: ± 3.7 percent for onion, ± 4.8 percent for pepper, and ± 3.5 percent for spinach.

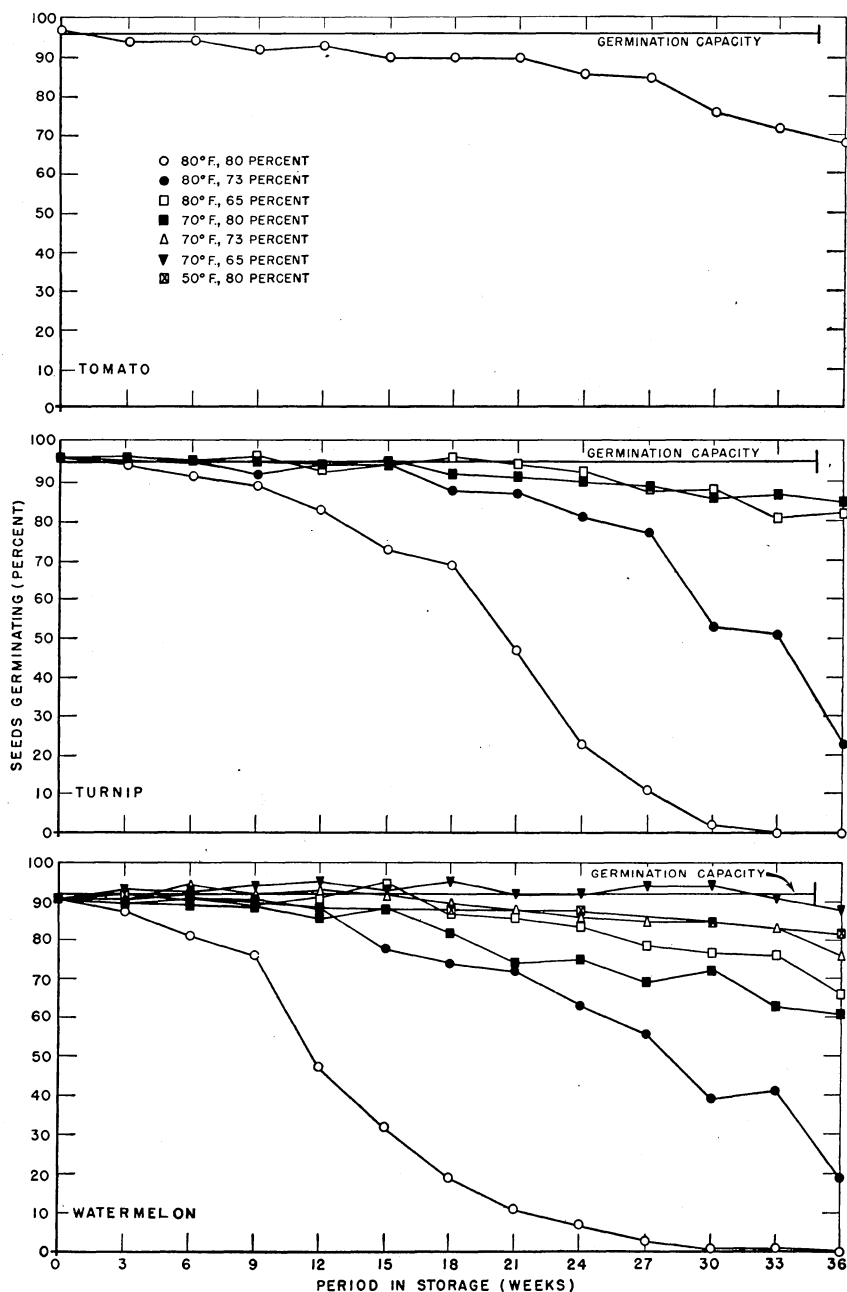


FIGURE 6.—Germination of tomato, turnip, and watermelon seeds after storage for 3 to 36 weeks at various temperatures and humidities. Germination capacity (horizontal line) determined from the mean value of tests before storage and of tests from conditions without significant loss of germination within the 36-week period. Amount necessary for a highly significant deviation from each mean: ± 2.8 percent for tomato, ± 3.1 percent for turnip, and ± 3.2 percent for watermelon.

For many kinds of seeds there was no significant decrease in germination during the 36-week period for 2 or more of the storage conditions. In the graphs all values representing no significant change have been combined into a single horizontal line (germination capacity) developed from the replicate tests made before storage and the successive tests from the conditions that showed no significant loss up to 36 weeks of storage. The standard deviations of these individual values were determined, and the amounts required for a highly significant deviation (99:1) from the mean of these values are indicated in each graph by a vertical line at the end of the horizontal line. These mean values vary in precision. For onion only 40 values (16 original plus 24 at 50° F. and 50 percent humidity) were available for calculation of the mean and the standard deviation, whereas for tomato 304 values were used. Successive germination values are plotted for only those storage conditions that showed significant decrease in germination within 36 weeks.

As the experiment was started in February, the temperatures under natural conditions at Beltsville for the first 18 weeks were favorable for maintaining seed viability and therefore the losses for the period of the experiment were not large. For this reason a detailed report of the germination of the seeds stored in the warehouse is not given. Onion and lettuce from warehouse storage showed an appreciable loss in germination early in the summer and a serious loss by the end of the storage period in October. Sweet corn, watermelon, cucumber, spinach, cabbage, carrot, celery, and pepper showed some loss by the end of the summer. Bean, pea, okra, turnip, and tomato maintained their viability under these natural conditions for the entire period of 36 weeks.

In practice, it is essential to know how long seeds can be held at known conditions until the loss becomes appreciable and until a serious loss is expected. For this purpose table 5 shows the approximate time seeds remained in storage at various conditions before a significant decrease in germination was observed and before germination fell below the minimum standards for vegetable seeds. The standards applying in interstate commerce as determined and established under the Federal Seed Act (9) were used.

Of the 15 kinds of vegetable seeds, onion (fig. 7) was decidedly the most sensitive to conditions of storage and tomato the least. None of the seeds decreased significantly in germination during 36 weeks of storage at 50° F. and 50 percent humidity. Sweet corn, pepper, watermelon, onion, and celery decreased significantly at 50° and 80 percent humidity, and the last 3 kinds also showed a significant loss at 70° and 65 percent humidity. The relative keeping qualities of different kinds of seeds cannot be rated definitely, because of their unlike response to the various storage conditions. For example, onion seed stored at 80° and 80 percent humidity decreased in viability appreciably in 3 weeks and was entirely dead in 12 weeks, whereas lettuce seed held its original viability for 6 weeks but then decreased in germination almost as rapidly as onion. Under the conditions of this experiment, onion seed was protected from a significant loss only

TABLE 5.—Time in storage until first highly significant decrease in germination and until germination fell below accepted standards

[When no value is given the subminimal one was not reached in the 36-week period of the experiment]

Kind of seed	Time at indicated temperature and humidity of storage for—																		Germination standard ¹		
	First highly significant loss of germination									Decrease in germination below standard ¹											
	80° F.			70° F.			50° F.			Ware-house	80° F.			70° F.			50° F.			Ware-house	
	80 per cent	73 per cent	65 per cent	80 per cent	73 per cent	65 per cent	80 per cent	50 per cent	80 per cent		73 per cent	65 per cent	80 per cent	73 per cent	65 per cent	80 per cent	50 per cent				
Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Weeks	Percent		
Bean, snap	12	18	33	24	30				36	12	21								75		
Cabbage	6	15	18	18	24				36	12	21	30	36						75		
Carrot	6	15	24	12	24				36	12	24								55		
Celery	3	6	18	6	18		30	30	30	6	12	24	18	24				36	55		
Corn, sweet	6	15	30	18	30		30		33	6	15	30	18	33		36		33	75		
Cucumber	6	15	30	24	30				30	12	30								80		
Lettuce	9	12	21	18					21	12	24	30						36	80		
Okra	9	27		33					21	21									50		
Onion	3	6	9	6	9	24	24		21	6	9	15	18	24				30	70		
Pea	12	18	33						18	18	33								80		
Pepper	6	18	21	24	33		36		27	18	30								55		
Spinach	6	12	15	15	21				30	12	18	24							60		
Tomato	15									33									75		
Turnip	6	18	27	21						15	27								80		
Watermelon	3	15	18	12	21	36	18		30	12	24	36	33						70		

VEGETABLE-SEED STORAGE

¹ Standards applying in interstate commerce as published in U. S. Prod. and Market. Admin. Serv. and Regulat. Announc. 156 (9).

at 50° and 50 percent humidity (fig. 7, *H*), but lettuce seed showed no loss even at 70° and 73 percent humidity.

Loss of viability of all kinds of seeds was progressively faster with increase of temperature or of humidity and the effect of the two factors was additive. For this reason, it cannot be said that one is a more important factor than the other—they must be considered together.

The germination graphs indicate a general tendency for a similar rate of loss in germination for storage at 80° F. and 65 percent humidity and at 70° and 80 percent humidity. This is particularly true for the kinds of seeds that did not decrease sharply in viability at these

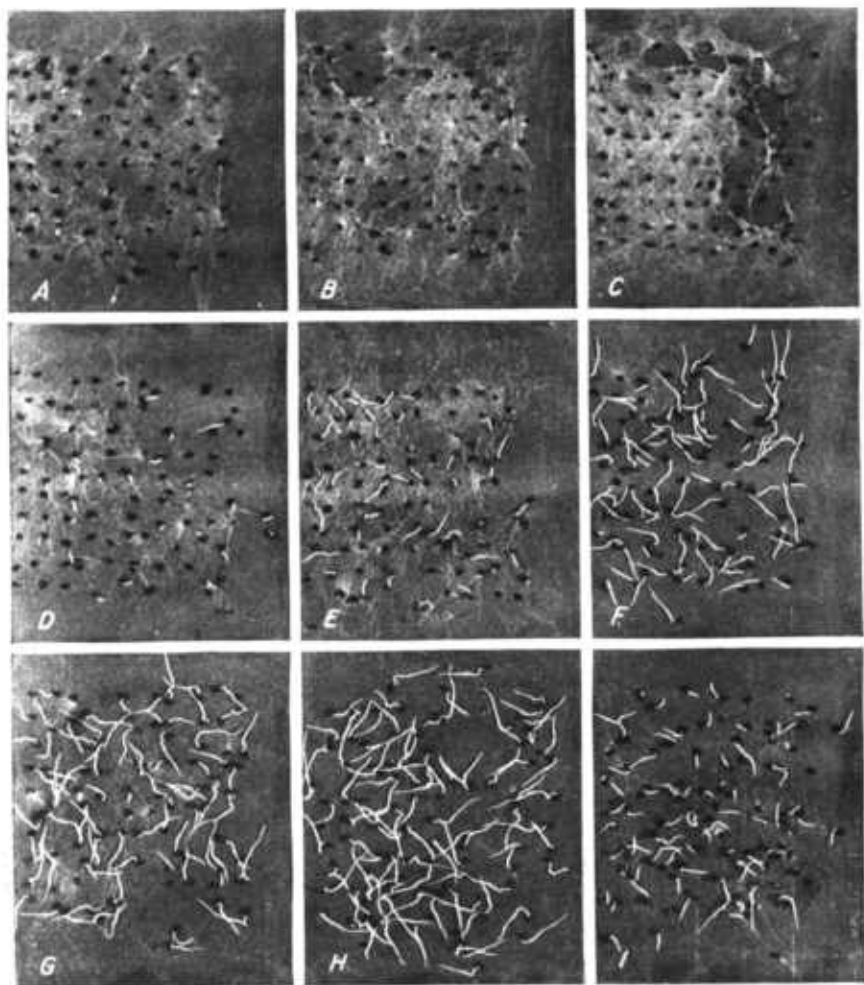


FIGURE 7.—Germination of onion seed stored for 36 weeks under various conditions of temperature and humidity: A, 80° F. and 80 percent; B, 80° and 73 percent; C, 80° and 65 percent; D, 70° and 80 percent; E, 70° and 73 percent; F, 70° and 65 percent; G, 50° and 80 percent; H, 50° and 50 percent (best condition); I, warehouse.

conditions and for the early period of storage of those that deteriorated rapidly. However, there is a tendency for a more rapid decrease in germination at the higher temperature during the late weeks of storage. This is most marked for onion, lettuce, and spinach, all of which decreased in germination more rapidly than the other seeds. From this it may be suggested that to compensate for an increase of 10° in the storage temperature the humidity should be reduced more than 15 percent.

It would be expected that the original vitality of the seed and the presence or absence of contaminating micro-organisms would influence the rate of deterioration at unfavorable storage conditions. Fungus contamination was prevalent in the samples of corn, watermelon, and celery used in the present study; doubtless this is related to their great loss of viability at high humidity at all temperatures.

After the period of experimental storage, portions of the samples that had been held in cold storage for varying periods were retested, all of one kind on the same day. In general, the retested samples averaged slightly lower in germination than those tested at successive intervals immediately after removal from the original storage conditions. A more detailed analysis of the results showed that if the original storage conditions had not resulted in serious loss of viability, there was no significant difference in the two sets of germination values. However, if the original storage conditions had resulted in appreciable loss of viability and the sample had been held in cold storage for a month or more, germination in the retest was slightly but significantly lower than that in the original test.

Because of this consistent difference in some of the samples, the results of the retest were not combined with those of the original test. The retests did serve, however, as a general corroboration of the original values. In several instances the retest of lettuce gave markedly higher values than the original test. These values have been substituted for those of the original test.

Because only one sample of each kind of seed was used in the present experiment, it is of interest to compare the results obtained with those reported by Boswell et al. (4). Onion, cabbage, carrot, spinach, sweet corn, bean, and tomato were included in both the present study and the previous one. Storage at 80° F. and 80 and 65 percent humidities is somewhat comparable with storage at 80° and 78 and 66 percent humidities in the previous work. The periods of storage are not exactly comparable, however, because in this study the seeds were removed from storage after 21, 42, 63, 84, and 105 days, respectively, rather than after 20, 40, 60, 80, and 110 days as in the previous one.

The tomato seed did not decrease in germination sufficiently for a comparison to be made. The cabbage seed was of about the same original quality in both experiments, and its response to storage conditions was practically the same. The two samples of sweet corn were also of comparable viability; their response at the higher humidity was similar, although in the first experiment there was a greater early loss of viability; at the lower humidity the present sample did not decrease in germination in 105 days, but the earlier one showed a loss of 18 percent in 110 days. Spinach and onion seeds showed a greater loss at the higher humidity in the first experiment; both kinds

of seeds used in that experiment had a lower original germination. The samples of carrot and bean seeds had lower original germinations in the present experiment, and both showed a somewhat greater decrease in germination. The general response of these seven kinds of seeds was similar in the two experiments, although there is an indication that seeds of high original vigor do not decrease in germination so rapidly as those of lower original vigor.

RATE OF GERMINATION

Kearns and Toole (7) have pointed out for fescue seed that under adverse storage conditions the first visible result of loss of viability is a slowing of the germination process. This retardation is more apparent when loss in viability is moderately rapid. A weakened condition of a sample may often be detected by the rate of germination before there is any loss of total germination of normal seedlings.

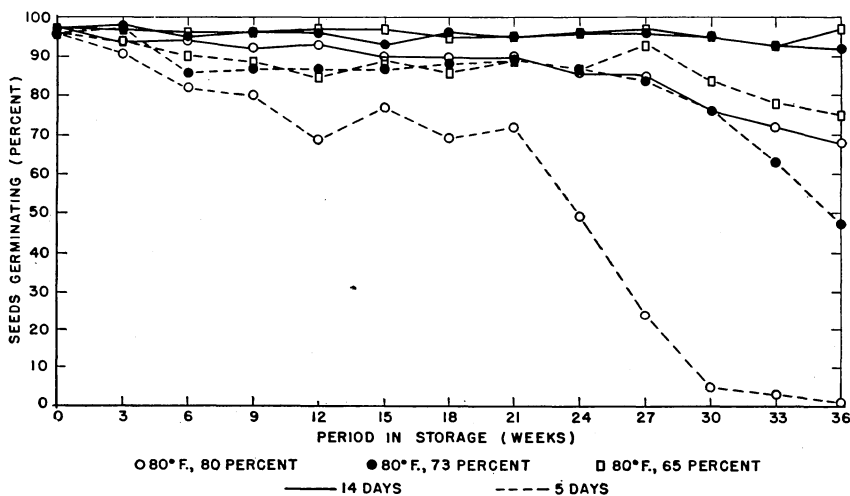


FIGURE 8.—Rate of germination of tomato seed from different storage conditions, shown by comparison of the germination in 5 days with the final germination in 14 days.

This reduced vigor can be expected to be followed by a decrease in germination. For example, tomato seed showed no significant loss in 36 weeks of storage at 80° F. and 73 percent humidity when the final readings were made, yet 45 percent of the germination occurred between the fifth and fourteenth day (fig. 8), while the germination of the seed stored at this same condition for only 3 weeks was practically completed on the fifth day. It has been pointed out that tomato is the most tolerant of the seeds studied to storage condition and that onion is the most sensitive. Figure 9 shows the rate of germination of onion seed from a few of the storage conditions. It also shows a loss of vigor that is accompanied more closely by a loss in total germination. Watermelon and pea seeds showed a response similar to onion. The pepper seed was slow to germinate when tested before

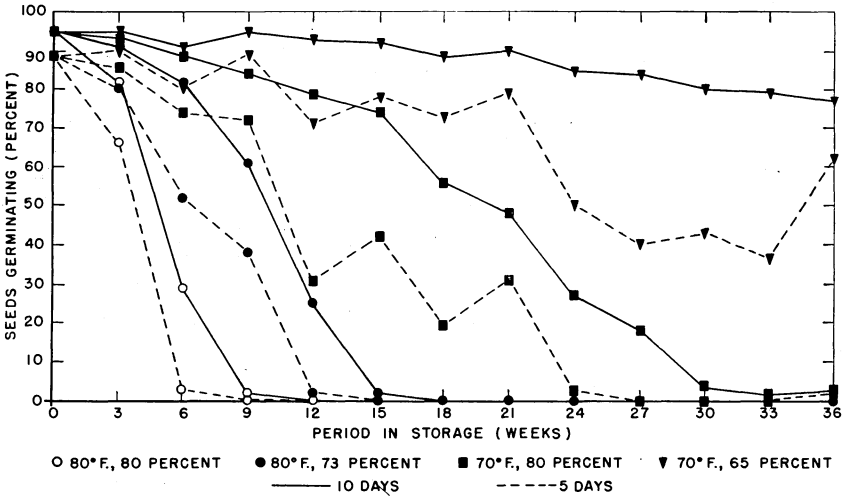


FIGURE 9.—Rate of germination of onion seed from different storage conditions, shown by comparison of the germination in 5 days with the final germination in 10 days.

it was put in storage, and it continued to be slow throughout the experiment (fig. 10). However, the seed at 80° was slower to germinate than that at 70°. All the conditions are not given in the graph, but for a given temperature the rate of germination was much the same for the three humidities. The line for the preliminary counts varies more than that for the final. Small differences in moisture in the germination substratum can induce very marked differences in the rate of germination that largely disappear in a few days.

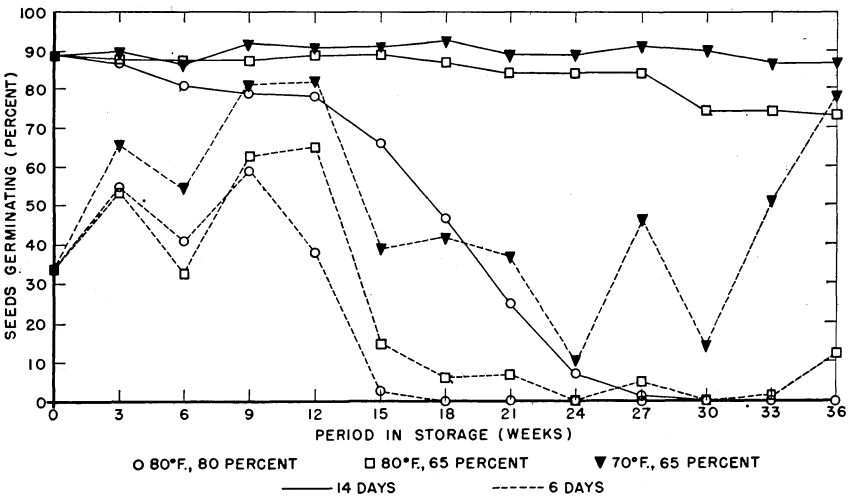


FIGURE 10.—Rate of germination of pepper seed from different storage conditions, shown by comparison of the germination in 6 days with the final germination in 14 days

A change of germination rate not dependent on change of vitality was observed in germinating the stored seed of okra. A variable proportion of the seeds of okra, in common with those of other members of the Malvaceae, have impermeable seed coats. It has been suspected by the writers that in okra the proportion of such seeds varied inversely with moisture content. Apparently a humidity of approximately 50 percent was not low enough to bring about a marked degree of impermeability, but the results of the germination tests suggest that decreasing air humidity induced progressive changes in the seed coats that resulted in progressively slower water absorption and slower rate of germination. The average germination of okra seed in 4 days as compared with that in 14 days for seed from several storage conditions is shown in table 6. The germination percentages were averaged only for the period during which there was no significant loss of viability for the given condition. Although the germination in 4 days was rather variable for any given condition, there was no evidence of progressive change in the rate of germination over the period of storage considered. The rate of germination seems to be directly proportional to the moisture content of the seed. This effect of humidity during storage and of moisture content of seed on rate of germination was not observed on other kinds of seeds in this study.

TABLE 6.—Average rate of germination of okra seed after storage under various conditions

Average temperature during storage (° F.)	Average humidity during storage	Germination tests averaged	Average moisture content of seed	Average germination in—	
				4 days	14 days
	Percent	Number	Percent	Percent	Percent
52.1.....	52.4	6	10.4	14.5	87.3
71.4.....	64.5	12	11.3	25.6	87.6
80.4.....	65.8	11	11.8	35.7	86.4
70.7.....	73.3	12	12.7	72.5	86.2
80.3.....	73.4	7	12.8	75.5	86.5
51.7.....	80.1	6	15.4	86.6	87.7
70.3.....	80.5	9	13.7	82.7	85.1

PRODUCTION OF ABNORMAL SEEDLINGS

It has been pointed out by Edwards (5) that all seeds within the population of a seed kind do not have the same temperature response. It is demonstrated here that all seeds of a population of one kind are not equally affected by adverse storage conditions. Within a population of a seed kind there are a few seeds that will produce normal seedlings after storage for a long time under adverse conditions; some will be completely killed after a short period of storage; and others will produce seedlings having some one tissue or organ, as the root tip or the stem growing point, dead before the death of other parts of the seedling. Such local deterioration may result in a weakened seedling capable of recovery or in a seedling that is incapable of further development and of no value in crop production. Injured seedlings present

a serious problem in the evaluation of the results of a germination test, since often there is no sharp line of distinction between weakened seedlings capable of recovery and those not capable of producing a useful plant. Also, there is a great variation in different species in the proportion of abnormal growths encountered.

During storage comparatively little change occurred in the number of abnormal seedlings produced by carrot, celery, and pepper seeds. The percentage of abnormal sprouts was less than 5 percent in the original tests for these three kinds of seeds. During the 36-week period the percentage of abnormal sprouts never exceeded 5 percent in carrot and pepper and 10 percent in celery. Most seeds of these three vegetables were either killed outright or produced normal seedlings. Cabbage, cucumber, garden pea, watermelon, and okra seeds, however, produced rather high percentages of abnormal sprouts. Seeds of spinach, onion, lettuce, and turnip produced higher percentages of abnormal sprouts than the other kinds tested. Lettuce probably presents the most difficult interpretation problem. Lack of vigor in lettuce seed shows up in the inability to shed the seed coat and in the occurrence of spotted cotyledons. Also, although lettuce seeds may produce all the essential organs, they are subject to some physiological break-down indicated by glassy, watery sprouts. Difficult interpretation problems are also presented by turnip and cabbage seeds, because of the presence of such sprouts. The most common abnormality in onion, cucumber, watermelon, and okra is the lack of root development. In spinach the abnormalities usually consist of a lack of a root or a shoot.

Stored spinach seed produced many types of abnormal seedlings encountered in commercial samples. When tested before storage or after storage at conditions that did not injure viability, the sample of spinach seeds used produced only about 2 percent of abnormal seedlings. Figure 11 shows for different storage conditions the percentage of normal seedlings (those believed capable of continued development and counted as germinated) and abnormal seedlings (those believed not capable of development into plants and not included in the germination percentage) produced by spinach, lettuce, and onion. For spinach (fig. 11) at the three humidity conditions at 80° F., where deterioration was comparatively rapid, there was a gradual increase in the percentage of abnormal seedlings until 35 percent or more were present, and then there was a decline as the sample approached absolute loss of life. At 50° and 50 percent humidity, however, there was no appreciable change in the percentages of normal or abnormal seedlings during the 36 weeks of storage. Onion and lettuce also show that as the percentage of normal seedlings decreases the percentage of abnormal sprouts increases, so that when the results are plotted (fig. 11) the curves cross. These results emphasize that if storage studies are to indicate the decline in the useful value of the seed, care must be exercised to make sure that seedlings are not counted and removed before they have developed to an extent that will definitely show their possibilities of future growth.

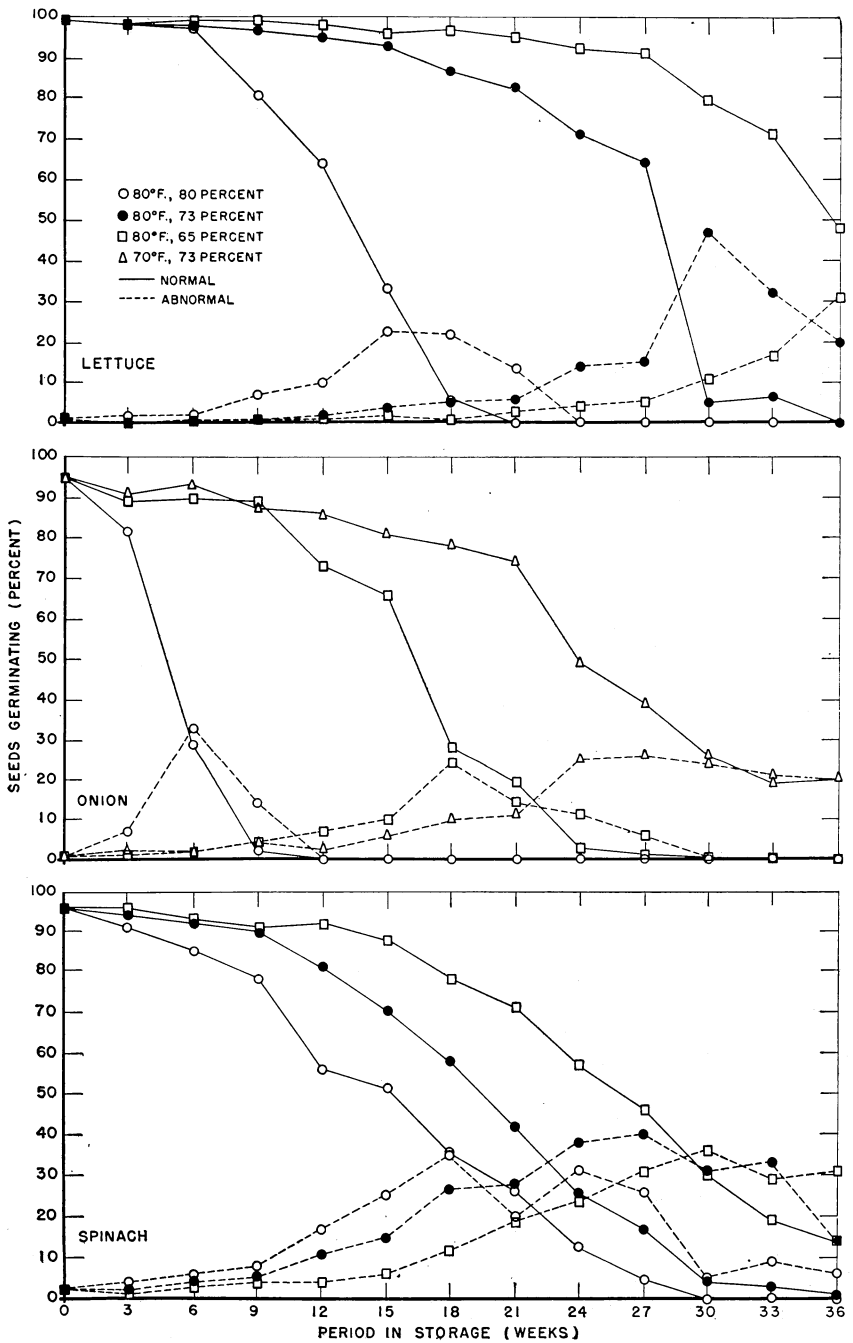


FIGURE 11.—Comparison of the increase in percentage of abnormal seedlings of lettuce, onion, and spinach with the decrease in percentage of normal seedlings at successive tests during storage at different temperatures and air humidities.

COMPARISON OF SEALED AND OPEN STORAGE

A total of 98 comparisons was made of the germination of seeds from sealed and open storage. The number of comparisons varied from 0 for sweet corn to 11 each for celery and onion. Apparently the seeds dried somewhat in the process of sealing, since in all but 6 of the comparisons the moisture content of the seeds when the vials were opened was lower than it was before they were sealed. For 73 of the 98 comparisons the moisture content of the seeds when removed from the sealed vials was slightly lower than that of the seeds in open storage from the sixth week until the time of comparison. For 80 of the 98 comparisons the germination was higher for seeds from sealed storage than for those from open storage; 36 of the 80 comparisons showed a difference of more than 10 percent. Part of this apparent superiority of sealed over open storage was probably due to the generally slightly lower moisture content of the sealed seeds. At the same time there was a tendency for higher germination of the sealed seeds that can hardly be accounted for on the basis of moisture content alone. It seems possible that the reduced oxygen supply resulting from sealing contributed to seed longevity. Certainly there is no evidence that sealing seeds with moisture contents of the range shown in these studies caused them to deteriorate any faster than seeds of equal moisture contents exposed to open air. Seeds that have been sealed with a high moisture content would not keep as well as if left in open air at a low humidity, where they could dry out.

SUMMARY AND CONCLUSIONS

Fifteen kinds of vegetable seeds—bean, cabbage, carrot, celery, sweet corn, cucumber, lettuce, okra, onion, pea, pepper, spinach, tomato, turnip, and watermelon—were stored in small containers at approximately the following conditions: 65, 73, and 80 percent humidities, each at 70° and 80° F., and at 50 and 80 percent humidities, each at 50°. Natural, or warehouse, storage was also provided. Seed moisture and germination were determined at 3-week intervals for a period of 36 weeks.

The mean moisture content of the seeds varied directly with air humidity, but it was influenced only slightly by temperature of storage. Both the equilibrium moisture content at a given humidity and the rate of change of moisture with change of humidity were different for the different kinds of seeds.

None of the kinds of seeds had decreased significantly in germination at 50° F. and 50 percent humidity by the end of 36 weeks. All kinds of seeds showed some loss of viability and nearly all kinds complete loss at 80° and 80 percent humidity by the end of the experiment.

Of the 15 kinds of seeds, tomato was the most resistant to unfavorable storage conditions and onion was the most sensitive.

The various kinds of seeds showed a different relative response to the several storage conditions, so that it is not possible to rate them definitely in the order of susceptibility to deterioration in storage. The results of this experiment are in good agreement with those previously reported by Boswell et al. (4) for the kinds of seeds and conditions that are included in both experiments.

Many kinds of seeds showed a decrease in rate of germination before there was a definite loss of viability. With the samples of spinach, onion, lettuce, and turnip seeds used in this experiment a marked increase of abnormal seedlings not counted as germinated was observed in testing samples stored at unfavorable conditions. This was due to the death or weakening of some essential part of the embryo before all tissues were dead.

Seeds sealed at various moisture contents in glass vials generally retained their viability as well as, or better than, seeds at similar moisture contents that were exposed to the open air.

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