J. Amer. Soc. Hort. Sci. 105(3):298–303. 1980.

The Relationship of ATP Concentration to Germination and Seedling Vigor of Vegetable Seeds Stored under Various Conditions[1]

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Additional index words. Zea mays, Cucumis sativus, Allium cepa, Raphanus sativus, seed viability

Abstract. **The possibility of using seed adenosine triphosphate (ATP) content as an indicator of seed vigor was studied. Seeds of corn (*Zea mays* L.), cucumber, (*Cucumis sativus* L.), onion (*Allium cepa* L.), and radish (*Raphanus sativus* L.) with seed moisture contents of 5, 10, 15, 20, or 25% were stored at temperatures of −10°, 5°, 15°, 25°, or 35°C for 0, 2.5, 5, and 10 months. Germination and seedling vigor decreased as storage time, temperature, and moisture level increased. Viability was lost in most seeds after 2.5 months at high temperature (25-35°) and high moisture (20-25%) contents. Seed stored at 5° and 5% moisture maintained the highest viability and seedling vigor over the 10-month storage. Low temperature (−10°) and high seed moisture levels (20-25%) reduced germination and vigor of radish seed. Seed ATP content did not correlate with reduced germination or vigor in any species. ATP concentrations consistently decreased over the 10-month storage period in all seeds stored at −10°. However, this trend did not correlate with the other vigor indices.**

Seed vigor can be defined as "the sum total of all those properties in seeds which, upon planting, result in rapid and uniform production of healthy seedlings under a wide range of environment including both favorable and stress conditions" (11). Recently, a biochemical test which measures adenosine triphosphate (ATP) was reported to be effective in estimating vigor of seeds (5, 6). Significant correlations were found between ATP and vigor in lettuce, rape, ryegrass, and crimson clover seeds. This method of equating ATP content with seed and seedling vigor has not been adequately tested on seed lots of variable age stored under ideal and adverse conditions.

Seed viability and seedling vigor are affected by storage conditions. Barton and Garman (3) reported only 6% germination of tomato seeds stored for 13 years at room temperature and the resultant plants performed poorly in the field. Plants from seeds stored 13 years under dry conditions at −5°C were equal in growth rate to those from fresh seeds and germinability was 89%. They concluded that storage conditions (temperature and moisture) had a greater effect on growth of the subsequent seedlings than did seed age. Barton (2) stored seed of lettuce, tomato, and onion for 18 years at different temperatures and seed moisture contents. In all cases the first evidence of deterioration was reduced rate of germination. Seed with high vigor could be stored longer under less ideal conditions than seed with low vigor (1, 4).

The following experiment was designed to determine the relationship of ATP concentration after 4 hr imbibition to germination and seedling vigor of seeds of 4 vegetable species stored under various conditions of moisture and temperature.

Materials and Methods

Seed of 'Seneca Chef' sweet corn, 'Marketmore', cucumber, 'Fiesta' onion, and 'Cherry Belle' radish were obtained from Stokes Seed Ltd. All treatments used untreated seed of the same lot which was less than 1 year old. Germination and vigor measurements were taken before the seeds were stored.

Initial seed moisture content was determined by placing a 10-seed sample in a forced air oven at 105°C for 16 hr. Moisture contents were adjusted for each species by the method of Rocha (7). Quantities of seed were placed in small mason jars and their moisture contents adjusted by either drying in an oven at 35° or adding a measured amount of water to obtain seed moisture contents of 5, 10, 15, 20, and 25%. Each moisture content was replicated twice. After the moisture was adjusted, the jars were sealed and equilibrated at 22° for several days, after which moisture contents were readjusted if necessary.

Sealed jars were placed in incubators at temperatures of −10°, 5°, 15°, 25°, and 35°C. Duplicate samples of each replicate at each temperature and moisture content were taken at 0, 2.5, 5 and 10 months and ATP content, percent germination, and seedling vigor were measured.

The ATP extraction and buffering procedures were similar to those used by Ching and Danielson (6). To obtain a seed extract for ATP analysis, duplicate samples of 10 seeds of corn and cucumber, and 25 seeds of onion and radish were weighed, wrapped in paper moistened with distilled water and imbibed for 4 hr (6). After imbibition, seeds were crushed and placed in a test tube with 10 ml of boiling distilled water. Aluminum foil capped tubes were held at 100°C for 10 min and then cooled in an ice bath. Five ml of extract were mixed with 5 ml of buffer containing 0.05 M N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid (HEPES), pH 7.5, and 0.05 M magnesium acetate.

The ATP assay was previously described by St. John (8). Freeze-dried firefly extract containing luciferin-luciferase (Sigma Chemical Company) was reconstituted by adding 5 ml of ice-cold distilled water. The enzyme preparation, containing 0.05 M potassium arsenate and 0.02 M magnesium sulfate at pH 7.4 was incubated at 4°C for 16-24 hr to deplete endogenous ATP. Duplicate samples of 0.4 ml from the buffered seed extracts were pipetted into small test tubes. The enzyme preparation (0.1 ml) was injected into the tube and peak height of light production was recorded from an Aminco Chem-Glo Photometer. The ATP concentration corresponding to the unknown peak height was read from a standard curve and expressed as nmoles ATP per g fresh weight of seed.

For germination test duplicate samples of 50 seeds each from each replicate were rolled in paper towels which were incubated at 25°C for corn and cucumber and 20° for onion and radish. Germination counts were made after 1, 3 and 5 days for corn and cucumber, and after 3, 5 and 7 days for onion and radish. Germination rates were calculated according to the method of Shmueli and Goldberg (9). Radicle lengths were measured and fresh and dry weights were taken after 7 days for corn, cu-

[1]Received for publication June 2, 1979. Florida Agricultural Experiment Station Journal Series No. 1806. This research was supported in part by a grant from the American Seed Research Foundation.

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[2]We gratefully acknowledge the assistance of Dr. F. Martin, Statistics Dept., University of Florida.

cumber, and radish, and after 10 days for onion. Dry weights were obtained by drying seedlings in an oven at 70° for 48 hr. Fresh and dry weights were calculated on a per seedling basis.

Results

There were no definite trends in ATP content of sweet corn seed after 4 hr imbibition at any moisture level and sampling time over the temperature ranges used (Table 1). Measurable amounts of ATP were found in some ungerminated seeds (15°C and 20% moisture) indicating that seeds contained or could produce ATP even though they did not germinate. Seeds with high percent germination had low ATP contents. A consistent decline in ATP content over 10 months was observed in seeds at −10° and all moisture levels. This pattern was not evident at other temperatures. Germination was reduced during storage at −10° at 25% seed moisture in which case gerimination initially declined 2.5 months after storage. The ATP content of seeds stored at −10° and 25% moisture was higher than that of the other moisture regimes through 5 months storage even though germination had fallen off sharply. At 5% seed moisture, there was no reduction in germination at any temperature through 10 months. At 10% moisture, germination declined when seeds were stored at 25°C for 5 months with no germination at 35°C at 2.5 months or longer. As seed moisture content increased the percent germination fell off more sharply as temperature increased. Thus high seed moisture contents had a more negative effect on germination than did high storage temperatures.

Significantly higher amounts of ATP were measured after 2.5 months in cucumber seeds stored at 5°C, regardless of moisture content, than at any other temperature (Table 2). Large reductions in the amount of ATP in these seeds occurred after an additional 2.5 months. Germination, however, did not decrease appreciably until after 5 months of storage and then only at the 20% or 25% moisture levels. In seeds at −10°C, ATP contents declined considerably over 10 months storage at any moisture level. Measurable amounts of ATP were found in some ungerminated seeds. However, most non-viable seeds did not produce detectable levels of ATP. Germination occurred in seed stored for 10 months at 5% moisture over the temperature range. However, at 10% moisture, seeds at 25°-35°C lost viability with increasing storage time. This pattern persisted with seeds of higher moisture content stored at higher temperature until only seeds at −10° and 5° germinated. Even then the germination percentage declined at seed moisture contents over 10%.

The ATP content of onion seed at −10°C diminished during 10 months. irrespective of seed moisture content (Table 3). Highest ATP contents after 10 months were in seeds at 5° at all moisture levels. At 25°, onion seeds at 20 and 25% moisture had high levels of ATP after 2.5 months but did not germinate. Onion seeds did not germinate after 2.5 months at 15% moisture and 35° or 20% moisture and 25° or above. Except with moisture-temperature combinations of 15% and 25°, 20% and 15°, 25% and 15° germination remained high throughout 10 months of storage.

The ATP content was highest in radish seeds at 5°C after 10 months (Table 4). Decreasing concentrations of ATP were generally found over 10 months in seeds at −10°. The levels of ATP were lower at −10° than at 5°. Small quantities of ATP were detected in some seeds that did not germinate although most ungerminated seeds contained no measurable ATP. High germination was maintained at −10° and 5° with seed moisture contents 15% or below, but germination declined sharply with moisture contents over 20%, even though the ATP contents differed throughout these storage conditions. A reduction in germination occurred after 2.5 months at 15° at moisture levels of 15% or higher, and at all temperatures with 20% moisture or above. In most cases seeds did not germinate well after storage at 25° or 35° and moisture above 15%. Radish seeds did not germinate at −10° and 20 to 25% moisture.

Forty to 50% of corn, cucumber, or radish seeds did not germinate in 2.5 months (Table 5). This trend continued for the remainder of the experiment. Onion seed withstood storage conditions better: germination decreased only 25% at 2.5 months and did not change thereafter. Vigor measurements followed similar patterns in all of the crops. Germination rate decreased after 2.5 months with very little change thereafter. ATP decreased more after 5 months then after 2.5 months in every crop but radish. Radicle length averages decreased after 2.5 months for corn and radish and after 5 months for onion. The fresh weight of corn and cucumber seedlings increased as storage time increased to 5 months. Radish seedlings had higher fresh weights at 10 months. Onion fresh weights decreased after 2.5 months, then did not change further. Dry weights of cucumber, onion, and radish decreased with time to 10 months; dry weights of corn increased with 10 months in storage.

Table 1. ATP content and percentage germination in sweet corn seed stored under different conditions of moisture and temperature for 10 months.[z]

Moisture (%)	Time (months)	ATP (nmoles/g)					Germination (%)				
		−10°C	5°	15°	25°	35°	−10°C	5°	15°	25°	35°
5	2.5	4.8d[y]	7.2b	5.6c	5.2cd	18.8a	95a	95a	100a	100a	100a
	5	3.2b	2.4c	2.4c	4.8a	2.8bc	90b	100a	100a	95ab	95ab
	10	0.8d	4.8b	7.2a	4.4b	3.2c	95a	95a	100a	100a	100a
10	2.5	5.6b	6.8a	4.4c	5.2b	7.2a	100a	95a	95a	95a	0
	5	2.8b	2.4b	2.8b	4.4a	0	100a	95ab	90b	80c	0
	10	0.8b	7.2a	7.2b	1.2b	0	100a	95a	100a	85b	0
15	2.5	4.8d	8.0a	6.0c	6.8b	0	95a	95a	85b	60c	0
	5	3.6ab	3.2bc	4.0a	2.8c	0	90a	95a	40b	0	0
	10	0.8b	4.4a	4.0a	0	0	85a	70b	30c	0	0
20	2.5	6.0b	9.2a	6.0b	4.4c	0	95a	90a	0	35b	0
	5	3.6a	4.0a	0	0	0	80a	85a	0	0	0
	10	0.4b	4.0a	0	0	0	95a	35b	0	0	0
25	2.5	10.8a	7.6b	0	0	0	15b	55a	0	0	0
	5	5.2a	3.6b	0	0	0	15a	10a	0	0	0
	10	0.8b	2.8a	0	0	0	5ab	10a	0	0	0

[z]Before storage germination was 100% and the seeds contained 6 n moles/g ATP after 4 hr imbition.

[y]Mean separation within rows by Duncan's multiple range test, 5% level.

Table 2. ATP content and percentage germination in cucumber seed stored under different conditions of moisture and temperature for 10 months.[z]

Moisture (%)	Time (months)	ATP (nmoles/g)					Germination (%)				
		−10°C	5°	15°	25°	35°	−10°C	5°	15°	25°	35°
5	2.5	656c[y]	2640a	676c	284d	2400b	85b	95a	95a	95a	80b
	5	456a	360a	344a	516a	148b	95a	85b	100a	100a	95a
	10	120c	560b	804a	424b	488b	90b	95ab	100a	75c	90b
10	2.5	660c	4496a	696c	324d	1012b	80b	90a	80b	90a	15c
	5	424a	396a	432a	420a	0	100a	90b	95ab	80c	0
	10	76b	704a	668a	172b	0	100a	95a	70b	50c	0
15	2.5	500c	2084a	776b	452c	24d	95a	90a	55b	0	0
	5	280b	432a	152bc	256b	0	80a	80a	35b	0	0
	10	56b	388a	264a	0	0	80a	85a	20b	0	0
20	2.5	476a	624a	224b	172b	0	90a	90a	0	0	0
	5	184a	228a	0	0	0	70a	50b	0	0	0
	10	48a	116a	0	0	0	70a	50b	0	0	0
25	2.5	416b	752a	140c	0	0	95a	95a	0	0	0
	5	324a	76b	0	0	0	25b	65a	0	0	0
	10	44a	36a	0	0	0	35b	45a	0	0	0

[z]Before storage germination was 97% and the seeds contained 712 nmoles/g of ATP.

[y]Mean separation within rows by Duncan's multiple range test, 5% level.

Increasing moisture content from 5 to 25% decreased viability of all crop seeds (Table 6). Seed vigor, determined by germination rate, ATP content, and radicle length also decreased as moisture increased to 25%. ATP level was generally highest in cucumber and lowest in corn on a per g basis. With increasing moisture, ATP content decreased in corn and cucumber, remained relatively constant in radish, and increased at 25% moisture in onion. On the average, radicle lengths decreased as moisture levels increased from 5 to 25% and usually declined as germination decreased. Fresh weight of corn and cucumber seeds decreased with increased seed moisture content at 25%; fresh weight of onion and radish seeds were unchanged. Seedling dry weights were generally unchanged at all moisture contents, except with onion where dry weight increased at 25% moisture. All seeds maintained the highest germination and vigor when stored at 5% moisture.

Germination decreased in corn, cucumber, and radish seed regardless of temperature when the seeds were stored for 2.5 months or more (Table 7). Germination and vigor of onion seed were reduced by storage temperatures of 25° or 35°C. Viability and vigor were reduced at 15° or higher in the other 3 seeds. Germination and radicle length averages of radish were reduced at −10° as compared to 5°. In the other 3 seeds, germination rate, ATP content, and radicle length decreased as storage temperature increased. Seedling fresh and dry weights remained constant except in onion at higher temperatures.

Table 3. ATP content and percentage germination in onion seed stored under different conditions of moisture and temperature for 10 months.[z]

Moisture (%)	Time (months)	ATP (nmoles/g)					Germination (%)				
		−10°C	5°	15°	25°	35°	−10°C	5°	15°	25°	35°
5	2.5	268b[y]	188c	280b	564a	236bc	90ab	95a	85bc	95a	80c
	5	172a	192a	216a	212a	208a	100a	100a	95a	95a	95a
	10	32c	452a	240b	200b	220b	95ab	95ab	100a	90b	95ab
10	2.5	252b	228b	276ab	332a	236a	100a	95ab	90b	90b	90b
	5	240a	240a	256a	256a	272a	95ab	95ab	100a	90b	100a
	10	44d	336a	260b	128c	248b	100a	100a	100a	85b	95a
15	2.5	552a	256a	256c	428b	0	95a	100a	100a	75b	0
	5	280a	232a	252a	160b	0	100a	100a	90b	50c	0
	10	60c	380a	208b	52c	0	95a	95a	85b	50b	0
20	2.5	620a	300b	272b	240b	0	100a	100a	100a	0	0
	5	304a	256ab	208b	20c	0	100a	90b	75b	0	0
	10	76c	340a	180b	0	0	95a	95a	85b	0	0
25	2.5	1096b	1568a	656c	1140b	0	90b	100a	80c	0	0
	5	660a	300b	344b	120c	0	100a	95a	70b	0	0
	10	140c	1348a	260b	0	0	90a	95a	70b	0	0

[z]Before storage germination was 100% and the seeds contained 392 nmoles/g of ATP.

[y]Mean separation within rows by Duncan's multiple range test, 5% level.

Table 4. ATP content and percentage germination in radish seed stored under different conditions of moisture and temperature for 10 months.[z]

Moisture (%)	Time (months)	ATP (nmoles/g)					Germination (%)				
		−10°C	5°	15°	25°	35°	−10°C	5°	15°	25°	35°
5	2.5	184c[y]	608a	320b	588a	156c	65c	90a	90a	95a	80b
	5	72a	92a	76a	96a	76a	82ab	80b	90a	80b	65c
	10	44d	716a	248b	140c	116c	85b	75c	95a	90ab	85b
10	2.5	88c	176b	148b	288a	196b	95a	85bc	80cd	75d	85bc
	5	100a	64a	108a	88a	100a	65b	95a	70b	95a	45c
	10	44c	600a	176b	168b	168b	85ab	80b	90a	80b	55c
15	2.5	112c	252b	432a	108c	0	90a	85c	70b	35c	0
	5	76a	80a	64a	12b	0	85a	80a	65b	25c	0
	10	16b	256a	44b	0	0	80a	60c	70b	0	0
20	2.5	100b	1504a	20c	0	0	10b	70a	0	0	0
	5	72b	180a	0	0	0	0	65a	0	0	0
	10	0	568a	0	0	0	0	75a	0	0	0
25	2.5	568b	1052a	0	0	0	5b	60a	0	0	0
	5	76b	200a	0	0	0	0	40a	0	0	0
	10	0	500a	0	0	0	0	35a	0	0	0

[z]Before storage germination was 93% and the seeds contained 1164 nmoles/g of ATP.

[y]Mean separation within rows by Duncan's multiple range test, 5% level.

Table 5. Main effects of storage time on viability and vigor of vegetable seeds.[z]

Crop	Time (months)	Germination (%)	Germination rate index	ATP (nmoles/g)	Radicle length avg (cm)	Seedling wt	
						Fresh (mg)	Dry (mg)
Corn	0	100a[y]	3.5a	6.0a	7.9a	646b	104b
	2.5	60b	2.8a	5.6a	4.5a	628b	112ab
	5	50c	2.5b	2.4b	6.5b	742a	116a
	10	48c	2.2b	2.0b	4.3c	713a	119a
Cucumber	0	97a	4.5a	712a	3.0b	95d	21ab
	2.5	57b	3.1b	812a	2.5b	144c	22a
	5	50bc	2.8bc	216b	7.1a	336a	18c
	10	46c	2.5c	200b	3.0b	193b	19bc
Onion	0	100a	4.5a	392a	4.0a	35a	2.0b
	2.5	74b	3.3b	408a	3.3ab	27b	1.9a
	5	73b	3.4b	212b	2.8b	27b	1.7b
	10	73b	3.6b	208b	2.3b	27b	1.4c
Radish	0	93a	4.1a	1164a	12.2a	103b	6.5a
	2.5	51b	2.5b	280b	7.0b	106b	6.4a
	5	45b	2.1b	64c	5.0c	102b	6.0a
	10	44b	2.4b	152bc	4.8c	114a	4.5b

[z]Data averaged over all storage temperatures and moisture contents.

[y]Mean separation in columns by Duncan's multiple range test, 5% level.

All seeds appeared to store best at 5°, and all except radish at −10°. Although germinability was similar in seed at −10° to that at 5°, ATP values were lower in seeds stored at the freezing temperature.

General correlation coefficients. Seedling dry weight was the only vigor index that correlated significantly with ATP content in corn (Table 8). In cucumber, ATP content was positively correlated with GRI but negatively correlated with RLA and seedling fresh weight. ATP content was not correlated to any of any germination or vigor indices in onion or radish. ATP content did not correlate significantly with germination percent in any of the seeds.

Discussion

As storage temperature increased, seeds of corn, cucumber, onion, and radish lost germinability and vigor. Onion seed, however, was not so adversely affected by storage conditions. Seeds at −10 or 5°C and 5 or 10% moisture generally maintained the highest percentage germination and vigor. The freezing temperature reduced viability at high moisture levels in radish seed. This reduced viability could have resulted from cellular damage which occurred when the higher moisture content seeds were stored at very low temperatures. ATP content was reduced in all seeds at −10°. No other germination or vigor index consistently decreased. Barton (2) found

Table 6. Main effects of storage moisture content on viability and vigor of vegetable seeds.[z]

Crop	Moisture (%)	Germination (%)	Germination rate index	ATP (nmoles/g)	Radicle length avg (cm)	Seedling wt Fresh (mg)	Seedling wt Dry (mg)
Corn	5	97a[y]	4.0a	5.2a	9.7a	712ab	110a
	10	75b	3.5a	4.0b	7.0b	732a	119a
	15	50c	2.5b	3.2bc	4.8c	620ab	116a
	20	34d	1.7c	2.4cd	3.2d	644ab	115a
	25	7e	0.6d	2.0d	0.9e	586b	117a
Cucumber	5	92a	4.8a	724a	7.7a	240a	20a
	10	69b	3.8b	700a	5.5b	233ab	21a
	15	41c	2.2c	376b	3.6c	210c	20a
	20	28d	1.6d	140b	2.6cd	215bc	18a
	25	24d	1.3d	112b	1.6d	187d	21a
Onion	5	94a	4.4a	244b	3.9a	28ab	1.6b
	10	95a	4.5a	240b	3.3ab	27b	1.7b
	15	70b	3.3b	208b	2.6bc	27b	1.7b
	20	56c	2.6c	188b	2.0c	27b	1.7b
	25	53c	2.4c	504a	2.2c	30a	2.0a
Radish	5	81a	4.0a	236a	9.2a	107ab	5.6a
	10	79a	4.0a	172ab	10.3a	115a	9.5a
	15	50b	2.4b	96b	5.3b	98b	6.3a
	20	15c	0.8c	164ab	2.1c	107ab	6.5a
	25	9c	0.6c	160ab	1.1c	102b	6.3a

[z]Data averaged over all storage temperatures and times.

[y]Mean separation in columns by Duncan's multiple range test, 5% level.

Table 7. Main effects of storage temperature on viability and vigor of vegetable seeds.[z]

Crop	Temperature (°C)	Germination (%)	Germination rate index	ATP (nmoles/g)	Radicle length avg (cm)	Seedling wt Fresh (mg)	Seedling wt Dry (mg)
Corn	−10	77a[y]	3.7a	3.6b	7.9a	664a	116a
	5	75a	3.7a	5.2a	6.5ab	649a	108a
	15	49b	2.3b	3.2b	5.2bc	718a	119a
	25	43b	1.9b	2.8bc	3.9cd	742a	124a
	35	20c	0.8c	2.0c	2.2d	735a	110a
Cucumber	−10	79a	4.2a	316b	7.2a	235ab	19b
	5	80a	4.4a	928a	6.5a	214bc	19b
	15	43b	2.3b	336b	3.2b	207c	19b
	25	33b	1.8b	200b	2.4bc	221abc	19b
	35	19c	1.0c	272b	1.6c	237a	25a
Onion	−10	96a	4.6a	320b	3.6a	29a	1.9a
	5	97a	4.5a	440a	3.9a	28a	1.4c
	15	89a	4.2a	272b	3.3a	25b	1.8ab
	25	48b	2.4b	256b	1.7b	27ab	1.7abc
	35	48b	1.6c	96b	1.8b	25b	1.6bc
Radish	−10	47b	2.3b	104b	7.0b	117a	6.7a
	5	72a	3.8a	456a	9.0a	103b	5.7a
	15	48b	2.3b	112b	5.3c	104b	5.1a
	25	38bc	1.9bc	100b	4.5c	111ab	6.0a
	35	28c	1.5c	56b	2.4d	111ab	9.7a

[z]Data averaged over all storage moisture contents and times.

[y]Mean seaparation in columns by Duncan's multiple range test, 5% level.

similar results when onion seed was stored at −18° with 22.3% moisture for 3 years. Germination was reduced for these seeds; seed stored at −2° germinated better.

Vigor measurements, such as germination rate, radicle length, and ATP content, declined with increasing time, temperature, and moisture levels. Decline in vigor generally paralleled decline in germination. However, there was not always a sharply defined place between loss or potential loss of viability and corresponding loss in vigor. For instance, ATP content usually did not correlate with changes in germination, germination rate, and radicle length of most seeds. Also, ATP was detected in ungerminated seed. Hence, reduction in germination was not always followed by reduction in the capacity of seed to synthesize ATP after 4 hr imbibition. This observation

Table 8. Correlation coefficients for germination and vigor indicators for 4 vegetable species where germination occurred.

Variable	Germination (%)	Germination rate index	Radicle length avg (cm)	Seedling wt (mg)	
				Fresh	Dry
			Corn		
ATP/g	.005	.187	−.186	.123	.239*
Germination (%)	−−	.665*	.336*	.065	−.366*
Growth rate index	−−	−−	.310*	.067	−.238*
Radicle length avg (cm)	−−	−−	−−	.372*	−.188
Seedling fresh wt (mg)	−−	−−	−−	−−	.147*
			Onion		
ATP/g	.088	.030	.125	.179	.164
Germination (%)	−−	.568*	.148	.229*	−.198*
Growth rate index	−−	−−	.080	.053	−.171
Radicle length avg (cm)	−−	−−	−−	.402*	−.020
Seedling fresh wt (mg)	−−	−−	−−	−−	−.172
			Cucumber		
ATP/g	.145	.232*	−.254*	−.261*	.187
Germination (%)	−−	.749*	.189	.107	.136
Growth rate index	−−	−−	.268**	.186	−.119
Radicle length avg (cm)	−−	−−	−−	.945*	.325*
Seedling fresh wt (mg)	−−	−−	−−	−−	.227*
			Radish		
ATP/g	.076	.082	.007	.049	.085
Germination (%)	−−	.725*	.602*	.053	−.544*
Growth rate index	−−	−−	.493*	.131	−.428*
Radicle length avg (cm)	−−	−−	−−	.439*	−.159
Seedling fresh wt (mg)	−−	−−	−−	−−	−.392*

*Significant at 5% level.

is contrary to previous results. Ching and Danielson (6) found a significant correlation between ATP content and various vigor indicators in lettuce and Ching (5) obtained similar results using rape, ryegrass, and crimson clover seeds. Vigor indicators included seed and seedling size and weight.

Soffer and Smith (10) found that seed weight was highly correlated to seedling vigor in lettuce. In our experiment, seedling fresh and dry weights were difficult to use as vigor indicators. Changes in fresh and dry weight of germinated seeds varied during the experiment. In corn, fresh and dry weight actually increased over 10 months storage. Apparently, only the most vigorous seeds germinated and these may have been the heaviest seeds. Therefore, when only individual seedlings were considered, seedling fresh and dry weight were not indicative of loss of vigor.

The ATP assay for seed vigor may be useful in some seeds under certain conditions. In seed lots where a large portion of seeds have no measurable germination, the ATP test might not be valid since vigor should only be measured on living germinable seeds. Previous publications (5, 6) related to ATP-vigor tests dealt with seed which had excellent germination and which were not stored under the extreme conditions of this experiment. It appears that seeds may lose vigor without completely losing the capacity to produce ATP. Thus, ATP may not be valid for comparing differences in vigor after only 4 hr imbibition, so tests should be conducted only on germinable seed.

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