Seed Quality and Storage of Soybeans

James C. Delouche
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The soybean became a crop of worldwide economic importance only in the last 20 to 25 years. In the United States, the biggest producer, the acreage devoted to soybean increased over 300 percent during the period 1952-1972. Brazil, the second largest producer, has enormously expanded its soybean acreage and production in just the last few years. The very rapid rise of the soybean to the forefront among world commercial crops is solidly based on continual improvement in cultivars and production technology, and is fully supported at every point by a parallel development of the infrastructure essential for commercialization of the soybean. An important element of this infrastructure—at least in the Western Hemisphere—is the soybean seed industry.

As an introduction to the subject of "seed quality and storage of soybeans," I believe it is informative to review briefly the development and present status of the soybean seed supply industry in the United States. It is recognized, of course, that the situation in the United States, where soybeans are produced on a vast acreage primarily for processing into animal feed, edible and industrial oils, other industrial products, or for export, is very different from that in most developing countries where soybeans are only now being introduced mainly as a high protein food crop for direct consumption. Nevertheless, the soybean is a seed-propagated crop regardless of how it is handled and ultimately used, and the developing countries beginning soybean production will be confronted with all the problems encountered in soybean seed production-supply in the United States. In the developing countries these problems generally will be much more serious and difficult to solve because of unfavorable climatic conditions.

Soybean farmers in the United States recognized early that soybean seed was somewhat different from the "seed" of most other crops with which they were familiar, e.g., maize, wheat, cotton, sorghum. Very often soybean seed germinated poorly even just after harvest, and germination further decreased during storage to the extent that, by the next sowing season, the seed was worthless for planting. Ordinary "seed saving" practices used by farmers for self-pollinated crops with "replacement" of the seed only every 3 to 4 yrs did not (and does not) work well for soybeans. Some farmers did learn to produce and store soybean seed of satisfactory quality through experience and installation of basic facilities, and some do save their own seed over several cropping seasons, but always with the option of obtaining the necessary planting seed from commercial sources or a neighbor whenever their own seed production efforts fail, which is rather frequent. Other soybean farmers, perhaps a majority, have turned increasingly to the specialized, professional seed producers and companies—the seed industry—for their entire seed supply.

Production of quality soybean seed is not without problems and risks even for the specialists and professionals. Their experience, facilities, and other resources, however, and their concentration on the single task of producing quality seed, have permitted the development of a responsible soybean seed supply industry capable of delivering moderate to good quality seed in quantities ample to meet the needs of soybean farmers.

The soybean seed industry in the United States consists of many seed companies located in all soybean producing states. This is necessary because soybean cultivars are rather narrowly adapted along north-south zones on basis of photoperiod, and within zones on the basis of a variety of factors including soil types, prevalence of diseases, and so on. Thus, seeds of specific cultivars generally must be produced within their area of adaptability. The seed companies involved in soybean seed production range in size from those which handle 10,000 to 15,000 bu per year (270 to 410 mt), to a few that market more than 500,000 bu annually (13,600 mt). Some of the seed is produced on land owned or otherwise controlled by the seed companies, but the largest portion by far is produced by
hundreds of private farmers under contractual agreements with the companies, or as independents with sales after harvest to the highest bidding company.

Compared to maize, rice, sorghum, millet, and some other important crops, the soybean has a low seed multiplication ratio. Seeding rate is rather high and yields are rather low, so that 3 to 5 percent or more of the total production must be saved for seed. The supply of seed needed for any sizeable acreage, therefore, is relatively large. In 1972 about 900,000 acres (360,000 ha) were used to produce "certified" soybean seed in the United States. The production from this acreage was sufficient to plant about one-third of the 1973 crop. The other two-thirds of the soybean crop were planted with noncertified seed (which is not necessarily inferior in quality to certified seed) obtained from seed companies, neighbors, or "saved" by the farmers from their own production. Although the purchase of certified or private "brand" soybean seed is increasing, it is estimated that currently about 40 to 50 percent of the United States soybean crop is planted with farm-saved seed or seed purchased from neighboring farmers.

An important characteristic of the soybean seed industry in the United States is its flexibility and responsiveness to seed crop failures and supply shortages. Almost every year, soybean seed production fails in some area within a state or region because of adverse climatic conditions during the growing, maturation, or harvest periods. In such instances soybean seed moves from areas with good production to the short-supply areas, generally along east-west lines.

It is hoped that this brief review of the development and present capabilities of the U.S. soybean seed industry has served to focus attention on the opportunities as well as the problems in establishing soybean seed production and supply operations in the developing countries, especially those in the subtropical and tropical zones.

ATTRIBUTES OF SEED QUALITY

Seed quality in soybeans encompasses several important attributes:

1. Genetic purity--cultivar purity is important from the standpoint of both total performance and uniformity, especially uniformity of maturity.

2. Physical purity--soybean seed should contain a minimum amount of inert material and should not be contaminated with seed of objectionable weeds and other crops.

3. Germination--high quality seed should germinate 85 percent or better.

4. Vigor--the germinable seed in a lot should be vigorous enough to emerge rapidly and uniformly under a broad spectrum of seed bed conditions and to develop into rapidly growing, productive plants.

Although the most chronic and difficult seed quality problems in soybeans relate to germinability and vigor, serious problems can also arise in connection with cultivar and physical purity. Aspects of soybean seed production connected with maintenance of cultivar purity are briefly discussed below.

MAINTENANCE OF CULTIVAR PURITY

Cultivar purity in soybeans is maintained through systematic seed multiplication and a rigorous in-company or in-department quality control program, or participation in the multiplication and quality control system of a seed certifying agency.

Certification procedures (9) designed to maintain cultivar purity and other quality standards during multiplication/production and processing of soybean seed include:

(a) Limitation on generations--multiplication of soybean cultivars is limited to two generations beyond the foundation seed generation, viz., registered class seed, which is the progeny of foundation seed, and certified class seed, which is the progeny of registered or foundation seed.

(b) Control of seed source--the seed used to plant each seed crop for certification must be of the proper class, e.g., registered class seed must be produced from registered or foundation seed.
(a) **Land history**—soybean seed cannot be produced on land on which the previous crop was another cultivar of soybeans, or the same cultivar but not certified, unless the cultivar planted can be easily distinguished from the one grown the previous season. This is to prevent cultivar contamination from volunteer plants.

(d) **Isolation**—soybeans are self-pollinated; nevertheless, fields of different cultivars of soybeans must be adequately separated (minimum of 3 to 4 m) to prevent mechanical mixtures.

(a) **Field standards**—soybeans subject to certification are field inspected at least once—usually at maturity—to determine that the ratio of plants of other cultivars to those of the cultivar certified does not exceed established standards (Fig. 1, 2).

(f) **Cleanliness of equipment and facilities**—threshing equipment and floors, drying facilities, bulk storage units, conveyors and cleaning machines must be thoroughly cleaned before use and between any change in cultivar. Selection of equipment for ease of cleaning, therefore, is an important consideration in design of seed processing facilities.

(g) **Seed standards**—after processing and packaging, certified class seed must not contain inert matter in excess of 2 percent, seed of other varieties in excess of 0.5 percent, and seed of objectionable weeds in excess of established limits. Minimum germination is usually 80 percent.

The foregoing are the minimum standards adopted by the Association of Official Seed Certifying Agencies. Individual country seed certification agencies may and do have more rigorous regulations and higher standards.

**FACTORS AFFECTING GERMINATION, VIGOR, AND STORABILITY**

The sources of germination and vigor problems that cause difficulties in soybean seed production and supply are diverse: inexperience of the many "new" producers; compromises between quantity and quality that are usually resolved in favor of quantity; over-extension of production beyond harvesting, bulk storage, and processing capacity; unfavorable weather during harvest period, and so on. The basic and most important source of seed quality problems in soybeans, however, and the one which directly or indirectly influences the occurrence and severity of nearly all other problems, resides within the soybean seed. The "modern" soybean is a marvelous packet of valuable chemical constituents, but as a reproductive unit it borders on being a failure.

**Seed Development and Morphology**

The structural and physiological delicacy of the soybean seed contributes in a major way to many germination and vigor problems. Some knowledge of seed development and morphology is essential, therefore, for understanding the complexity of factors involved in loss of germinability and vigor, and possible means of minimizing these losses.

Development of the soybean seed begins with fertilization (sexual). The two cotyledons and growing points are fully differentiated within the first 2 weeks. Dry weight of the developing seed increases slowly until about 20 to 30 days after flowering, depending on date of flowering (2), while moisture content (w.b.) slowly decreases from about 90 to 80 percent (Fig. 3, Lee cultivar). (Date of flowering--fertilization--has a pronounced effect on rate of seed development in a determinate variety such as Lee. Seeds from late season flowers develop much more rapidly than those from early season blooms. Seed set late in the season, therefore, "catches up" to that set earlier as the season progresses.) Beginning about 25 to 35 days after flowering, dry matter begins to accumulate rapidly in the seed reaching a maximum at 65 to 75 days. Thereafter, dry weight tends to remain constant or to decrease slightly (sometimes substantially when the seed is severely weathered prior to harvest). During the period of rapid dry matter accumulation, seed moisture content decreases rather slowly to 40 to 50 percent at the time maximum dry weight is attained. Under good field drying conditions seed moisture content then decreases from 40 to 50 percent to 15 to 18 percent in about one week.

Soybean seeds are physiologically mature at the time maximum dry weight is reached (40 to 50 percent moisture content). At this stage, germinability and vigor of the seed are highest even though the seed first becomes capable of germination when only about one-third of the dry weight has been accumulated.
The mature soybean seed is generally spherical in shape and has a relatively thin seed coat (Fig. 4). The hilum, point of attachment of the seed in the pod, is linear to elliptic in shape and located on the ventral face of the seed coat. It may be variously pigmented. The endosperm is represented only by a thin layer of cells immediately beneath the seed coat. The remainder of the interior of the seed is occupied by the embryo, which consists of a short radicle-hypocotyl axis, two fleshy cotyledons (lateral organs), and a well-developed plumule-growing point with two leaves, which is terminal on the radicle-hypocotyl axis and between the cotyledons.

The short radicle-hypocotyl axis is curved so that it lies against the basal margins of the cotyledons with its tip pointed in the same direction as the apices of the cotyledons. The position of the radicle-hypocotyl axis and the delicacy of the seed covering which is its only protection, makes the seed especially vulnerable to injury by mechanical abuse from any source—harvesting, conveying, processing, and so on. Since the radicle-hypocotyl axis is essential for normal germination, any substantial damage to it can be disastrous from the standpoint of seed quality.
Fig. 3. Moisture content and dry weight changes in soybean seed during maturation. MC, moisture content (w.b.); DW, dry weight per seed; G, 50 percent of seed capable of germination; M-1, physiological maturity of seed set from July 17 flowers; M-2, physiological maturity of seed set from August 6 flowers. From Andrews (2).

Fig. 4. Seed and seedling structure in soybeans. A, mature seed; B, seedling; C, embryo; a, seed coat; b, hilum; c, hypocotyl; d, plumule; e, cotyledon; f, primary root (radicle). Drawing from Delouche et al. (25).
Field Environment

The quality of soybean seed is very much affected by climatic conditions from the time the seed first drops below 25 percent in moisture during the postmaturation drying phase until the seed is harvested. Since the seeds are physiologically mature, they are in effect "stored" in the field during this period (17, 24).

Frequent or prolonged precipitation during the postmaturation, preharvest period results in alternate wetting and drying of the seed in the pod and severe deterioration. The dates in Table 1 are illustrative of the effects of adverse climatic conditions on moisture content and germination of soybean seed while it is still on the plant. After reaching "field maturity", i.e., harvestable stage on about September 20, Hill soybean seed fluctuated in moisture content from 11 to 20 percent depending on rainfall, while germination dropped to below 80 percent by October 6 and then further to 37 percent by November 3. The Bragg cultivar, which reached field maturity around October 23 or approximately one month later than Hill, also fluctuated widely in moisture content under the influence of rainfall, but loss of germinability was not nearly so severe. Bragg seed harvested on December 12 still germinated above 80 percent (Fig. 5).

The much greater reduction in germination of the Hill soybean seed as compared to seed of Bragg, even though subjected to fewer rains, can be attributed to the generally warmer temperatures in the area during the Hill weathering period. The effects of weathering on seed quality increase in severity as temperature increases. For this reason, germination problems of early maturing cultivars are more frequent and severe than for late maturing cultivars in temperate climates (19, 45).

The soybean seed producer cannot control climatic conditions during the harvest period but he can take several steps to limit both the extent and severity of weathering. Soybean seed should be harvested when it reaches field maturity (14 to 15 percent moisture) unless rainfall interferes. When rains delay harvest, seed producers equipped with adequate drying facilities can take advantage of any break in the weather. They need not delay harvest until moisture content drops back down to 14 percent or less.

Reduced seed quality in soybeans has also been associated with environmental conditions just the opposite of those discussed above. Hot, dry weather during harvest adversely affects both the physical and physiological quality of soybean seed (32, 33, 37).

Some efforts are being made to improve seed quality in soybeans through development of lines resistant to weathering and other environmental stresses during the maturation period (33, 34, 35, 57).

Harvesting and Threshing

In terms of seed quality, the harvesting and threshing process is probably the most critical phase of the over-all soybean seed production-processing operation. It is critical in three respects. First, improper cleaning of the combine and incautious operation are major sources of cultivar contamination. Second, timeliness of harvest is most important in minimizing field deterioration as mentioned above. Finally, mechanical abuse during harvesting and threshing operations is the most important cause of injury to soybean seed, commonly referred to as mechanical damage.

The adverse effects of inclement weather during the harvest period on seed quality have been discussed. It does not follow, however, that good drying weather completely eliminates quality problems. The opposite is all too frequently the case. Seed moisture content decreases rapidly when good drying weather prevails during the "normal" harvest time, or following a rainy period. In such cases, seed moisture may drop to 10 percent or less before harvest and threshing can begin or are completed. Very often the result is substantial seed injury even though harvest is done as carefully as possible.

Soybean seed becomes very brittle and susceptible to injury from mechanical forces when moisture content drops below 12 percent. Germination of soybean seed at 12 percent moisture or less can be immediately reduced as much as 10 percent by the force of an impact resulting from a 5 ft drop onto a metal surface, while a 20 ft drop onto the same surface has no immediate or latent effect on seed at 14 percent moisture content. The mechanical forces generated in the threshing section of a combine (Fig. 6, 7) and in certain types of conveyors are much greater than those resulting from a 5 ft or even a 10 ft drop (41, 44, 55).
Table 1. Effect of weathering on moisture content and germination of seed of the Hill and Bragg soybean varieties (25).

<table>
<thead>
<tr>
<th>Date of harvest(^a/)</th>
<th>Moisture content (%)</th>
<th>Germination (%)</th>
<th>Moisture content (%)</th>
<th>Germination (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/15</td>
<td>26</td>
<td>96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/22</td>
<td>13</td>
<td>97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/29+(^b/)</td>
<td>17</td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/6+</td>
<td>20</td>
<td>78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/13</td>
<td>11</td>
<td>76</td>
<td>26</td>
<td>98</td>
</tr>
<tr>
<td>10/20+</td>
<td>19</td>
<td>71</td>
<td>18</td>
<td>98</td>
</tr>
<tr>
<td>10/27</td>
<td>12</td>
<td>53</td>
<td>13</td>
<td>93</td>
</tr>
<tr>
<td>11/3+</td>
<td>14</td>
<td>37</td>
<td>14</td>
<td>92</td>
</tr>
<tr>
<td>11/10</td>
<td>12</td>
<td>92</td>
<td>12</td>
<td>92</td>
</tr>
<tr>
<td>11/17+</td>
<td>20</td>
<td>89</td>
<td>20</td>
<td>89</td>
</tr>
<tr>
<td>11/24+</td>
<td>13</td>
<td>86</td>
<td>13</td>
<td>86</td>
</tr>
<tr>
<td>12/1</td>
<td>15</td>
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<td>12/8</td>
<td>11</td>
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<td>84</td>
</tr>
<tr>
<td>12/15+</td>
<td>14</td>
<td>84</td>
<td>14</td>
<td>84</td>
</tr>
</tbody>
</table>

\(^a/\) Seed hand harvested and threshed, then cleaned with hand screens and aspirator before germination test.

\(^b/\) Date followed by + indicates one or more rains during preceding week.

Fig. 5. Weathering before harvest has a highly adverse effect on seed quality in soybeans. Above, periodic "sprinkling" treatments are being applied in an attempt to quantify the relationship between frequency and extent of precipitation, temperature, and degree of seed deterioration.
Fig. 6. Soybean seed can be severely injured during harvest when seed moisture content is low and the combine is not properly adjusted and operated.

Fig. 7. Soybean seed can be injured as badly with small plot threshers (below) as with large combine harvesters.
The most favorable seed moisture content for harvest of soybeans is a matter of some controversy. Available evidence (11, 19, 32, 41, 44, 46, 49, 52) suggests, however, that there is a rather narrow range of seed moisture contents that are optimal for harvest, between about 13 and 15 percent. Seed cracking and splitting increases sharply as moisture content decreases below 13 percent, while seed bruising and other less visible—but not less detrimental—injuries increase at moisture contents above 15 percent.

A few rules for harvesting as related to maintenance of seed quality are advanced below.

1. Weed-free, uniform stands facilitate adjustments of harvesters to minimize seed damage.
2. Commence harvesting when seed moisture content first drops below about 15 percent.
3. Combine at uniform ground speed.
4. Adjust clearance and cylinder speed so that complete threshing is achieved—but not higher.
5. When hand threshing is the practice, avoid strong forces, such as driving a tractor over unthreshed plants.
6. Check threshed seed periodically to determine extent of seed damage.
7. Weathering reduces resistance of seed to cracking and splitting; therefore, thresh weathered seed at higher moisture content 14 to 15 percent and avoid strong mechanical forces.

Handling, Bulk Storage, Aeration and Drying

Handling and conveying. All handling and conveying operations must be accomplished as gently as possible to minimize seed damage. For this reason, use of inclined augers for loading seed into bulk storage bins is not recommended. Loading of bins is best accomplished by "belt-veyors" or via the typical vibro-dump pit, belt-bucket, or continuous bucket elevator, horizontal drag flight, or belt conveyor, gravity spouting system (46, 55) (Fig. 8). The use of "dead boxes" in the longer gravity spout runs, to decrease velocity of seed flow and to absorb impact at points of directional change, and a "beam ladder" or spiral "letdown" inside the bin, contribute greatly to the high-quality soybean seed operation. Unloading of storage bins and conveying of seed to the processing plant are usually accomplished with short, horizontal unloading augers feeding onto or into a drag flight or belt conveyor.

Bulk storage and aeration. After harvest, soybean seed is usually stored in metal bins equipped for aeration or drying, or both, until the seed is processed and packaged (Fig. 9). The period in bulk storage ranges from a few weeks to about 6 months. Drastic reductions in germination and vigor can occur during the bulk storage period when seed moisture content is above 13 percent and the seed is not properly aerated or dried as necessary (12, 15, 19, 28, 39, 43, 46).

Aeration is usually adequate for conditioning and maintenance of seed viability at 13 percent moisture or less. Aeration equalizes temperature within the seed mass, prevents moisture migration, cools the seed to ambient temperature, and can reduce seed moisture content by 1 to 1.5 percent with higher air flow rates. Air flow rates of 0.1 to 1.0 cu ft of air per min (CFM) per bu are used for aeration. An air flow rate of near 1.0 CFM/bu is necessary to reduce seed moisture content by 1.0 to 1.5 percent as mentioned above. Aeration is best controlled with a humidistat set to cut off the fan whenever ambient relative humidity rises above 65 to 70 percent, which is in equilibrium with a seed moisture content of about 12.5 percent. The aeration system is turned off after the seed mass has cooled down and moisture content has stabilized. Thereafter, the system is activated periodically to prevent temperature stratification and moisture migration in the bin.

Drying. Soybean seed harvested above 14 percent moisture must be dried to 13 percent or less to maintain viability in bulk storage (6, 19). Natural air drying at flow rates of 3 to 5 CFM/bu are adequate for drying seed up to about 16 percent moisture. For seed at moisture contents above 16 percent, supplemental heat and higher air flow rates (6 to 9 CFM/bu) are usually necessary for effective drying. Depth of the seed for drying should not exceed 4 ft, and temperature of the drying air should not exceed about 30°C (Fig. 10).
Fig. 8. Side elevation (nonscaled) of a typical soybean seed facility. A, receiving area and dump pit; B, drag flight conveyor for loading bins; C, aeration-bulk storage bin; D, main receiving elevator; E, holding bin; F, surge bin and air screen cleaner; G, four-way continuous bucket elevator; H, surge bin and treater; I, surge bin and bagger-weigher; J, spiral separators; K, processing building; L, bagged seed storage building.

Fig. 9. Typical bulk storage bins used for storage and aeration of soybean seed.
Processing

Soybean seed moves from the bulk storage bins through the cleaning plant and into the packaged seed storage warehouse as the processing season progresses (Fig. 8). Basic cleaning is accomplished with an air and screen machine (19, 56). The air and screen machine removes fragments of pods, stems and seed, weed seed, immature seed, and other contaminants that are lighter, smaller, and larger than mature, intact soybean seed. Basic cleaning can increase germination percentage by a few points through removal of badly damaged, immature, and rotten (light weight) seed. In most cases basic cleaning is all that is necessary to prepare the seed for packaging and marketing.

Soybean seed is not difficult to clean. Most cleaning problems can be traced to attempts to "squeeze" too much capacity from the air and screen cleaner and other cleaners. It should also be pointed out that the cleaning machines, surge bins, and conveyors in the processing plant are potential sources of cultivar contamination. Therefore, the entire processing plant should be thoroughly cleaned at the beginning of the processing season and between any change in cultivar or seed kind during the processing season.

Treatment of soybean seed with a fungicide is beneficial, particularly when germination is less than 80 percent and the seed is infested with a disease such as pod and stem blight (7, 10). Only a relatively small proportion of soybean seed marketed, however, is treated because the risk of financial loss to the seedsman is too great. Once seed is treated with a fungicide it can only be used for planting purposes. Thus, seed that is not marketed for any reason, e.g., drop in germination below market standard, slow market, and so on, cannot be sold as grain; it must be dumped. For this reason, when soybean seed is treated with a seed protectant, the chemical is most frequently applied in the planter box.

The final step in processing is packaging. Soybean seed can be packaged in multi-wall paper bags, woven plastic bags, or burlap or cotton cloth bags.

Storage

The storage period for soybean seed begins at harvest (actually at the time seed reaches physiological maturity prior to harvest) and usually ends at planting time the following season. This period can be divided into two phases: the bulk seed storage phase, and the packaged seed storage phase. The former was discussed to some extent in connection with handling, aeration, and drying.
The longevity of seed in storage is influenced by four major factors: (a) inheritance of the species; (b) quality of the seed at the time it enters storage; (c) temperature of the storage environment; and (d) the moisture content of the seed or ambient relative humidity (17, 18, 19, 24, 28, 36).

Species. Soybean seed is inherently short-lived as compared to other major crop species (24). Under climatic conditions in the southeastern United States, germination percentage of the "average" soybean seed lot is maintained through May-June of the year following harvest (October-November), after which it begins to decrease, sometimes rather abruptly. Thus, germinability of soybean seed in the Southeast is just barely maintained through the first planting season following harvest. Seeds of corn, sorghum, cotton, and wheat, on the other hand, usually maintain germination through the second planting season following harvest, although seed vigor is often substantially reduced (Table 2).

In subtropical and tropical areas, the poor storability of soybean seed is a major constraint on production (24). The seed often drops in germination to the extent that it is worthless for planting within 2 to 3 months after harvest.

Quality of seed entering storage. The storability of seed is very much influenced by the degree to which the seed has deteriorated prior to storage. Soybean seed subjected to weathering before harvest, severely damaged during combining, and/or inadequately aerated during bulk storage does not store well even though it germinates moderately well at time of packaging (18, 19, 21, 28). Storage responses of two groups (A and B) of four lots each of soybean seed are given in Table 2 (20). The four seed lots of the A group were high in germination and vigor. The group B lots were considerably deteriorated before storage as a result of weathering and mechanical abuse. At the beginning of packaged seed storage in December 1968, average germination of the B lots was only 8 percent lower than that of the A lots. In the same storage environment, the difference in germination between the A and B lots increased to 29 percent by May 1969 (6 mos), 63 percent by August, and 71 percent by May 1970 (71 percent for A lots as compared to 0 percent for B lots).

Table 2. Comparison of germination percentages of different seed kinds during storage under ambient conditions, Mississippi State University, 1968-1970 (20).

<table>
<thead>
<tr>
<th>Kind of seed</th>
<th>Time in storage (mo)a/</th>
<th>0</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>18</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybeans A</td>
<td></td>
<td>90b/</td>
<td>91</td>
<td>86</td>
<td>84</td>
<td>71</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>62</td>
<td>23</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Soybeans B</td>
<td></td>
<td>98</td>
<td>98</td>
<td>99</td>
<td>98</td>
<td>97</td>
<td>90</td>
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<td>83</td>
<td>86</td>
<td>86</td>
<td>83</td>
<td>74</td>
</tr>
<tr>
<td>Cotton</td>
<td></td>
<td>94</td>
<td>91</td>
<td>95</td>
<td>92</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>Sorghum</td>
<td></td>
<td>94</td>
<td>91</td>
<td>95</td>
<td>92</td>
<td>90</td>
<td>82</td>
</tr>
</tbody>
</table>

a/ Period of storage: 12/68 through 11/70.
b/ Each datum represents average germination percentage of four "commercial" seed lots of each kind.

Temperature and moisture content. Seeds are hygroscopic. They absorb moisture from the atmosphere or lose moisture to it until the vapor pressures of seed and atmosphere reach equilibrium. Since the vapor pressure of atmospheric moisture at a specific temperature and pressure is a direct function of the degree of saturation or relative humidity, the various levels of seed attain characteristic moisture contents when exposed to different levels of relative humidity for sufficiently long periods of time. The seed moisture contents attained under these conditions are variously referred to as the equilibrium moisture contents, or hygroscopic equilibria. At 25°C, moisture contents of soybean seed in equilibrium with various levels of relative humidity are:
Seed storage studies or practical storage operations most often emphasize the controlling influence of relative humidity on seed moisture content. The hygroscopic equilibrium between seed and ambient relative humidity, however, is a two-way street. During the critical days following harvest when seed is in bulk storage and during any phase of storage involving moisture-vapor-proof packages, the controlling influence of seed moisture content on relative humidity of the immediate environment of the seed is paramount.

The relative humidity within a mass of soybean seed harvested at 16 percent moisture and loaded into a bulk storage bin is above 80 percent. And, it will remain at this level for a considerable period regardless of the outside relative humidity unless the seed is aerated. The relative humidity inside a 10 mil plastic bag of seed is similarly determined by the moisture content of the seed rather than vice versa.

It is important to consider both sides of the seed-moisture-vapor equilibrium because relative humidity within the seed mass has effects other than on seed moisture content. The growth and reproduction of storage fungi, which contribute to quality losses in seed and grain, are highly dependent on relative humidity within the seed mass (15). The more important storage fungi cannot grow and reproduce in seed or grain in equilibrium with a relative humidity less than 65 to 70 percent (12.5 percent moisture content in the case of soybeans). Activity of storage insects also drops sharply at relative humidities below 50 percent.

The temperature of the storage environment and within the seed mass also has a profound effect on maintenance of seed quality (18, 28, 36). In most instances temperature and seed moisture content (or relative humidity) interact closely in their effects on longevity of seed. High moisture content seed (e.g., 15 to 18 percent) can be stored for a year or more at a temperature of 10°C or less, while low moisture seed (9 percent or less) can withstand temperatures in the range 30°C to 35°C for the same period without substantial loss of germination.

The classic study of Toole and Toole (54) illustrates very well the effect of temperature and seed moisture content on the longevity of soybean seed in storage (Table 3). Germination of 9.4 percent moisture seed was maintained above 80 percent for more than 10 years at 10°C, for 5 years at 20°C, and one year at 30°C. In contrast, germination of 13.9 percent moisture seed decreased below 90 percent within 5 years at 10°C, 2 years at 20°C, and 0.5 year at 30°C.

Table 3. Effect of seed moisture content and temperature on germination percentage of soybean seed during storage (54).

<table>
<thead>
<tr>
<th>Moisture (%)</th>
<th>Temperature (°C)</th>
<th>Years in storage (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
<td>10</td>
<td>93 95 98 93 99 92 94</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>97 99 96 94 89 90 0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>96 87 0</td>
</tr>
<tr>
<td>13.9</td>
<td>10</td>
<td>95 98 96 92 88 49 0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>98 93 0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

In a more recent study conducted by Delouche and Baskin (20) in cooperation with a seed producer at Windfall, Indiana, soybean seed packaged at 9 percent moisture in either multi-wall paper or 7 mil polyethylene bags maintained germination through 40 months in a "cool" but unconditioned warehouse. Seed vigor, however, was substantially reduced after 24 months (Fig. 11).
For maintenance of both germination and vigor from harvest to planting (about 8 to 9 months) in temperate climates, soybean seed should be rapidly and properly conditioned to 12 to 13 percent moisture content after harvest, and stored over the winter in a dry, ventilated storehouse. In subtropical and tropical areas where the average annual temperature may be as high as 25°C, some type of moderately conditioned storage is usually necessary to maintain soybean seed quality. Air-conditioning a well-constructed storeroom so that temperature is maintained at 20° to 22°C or less, and relative humidity at 60 percent or less will usually maintain the quality of soybean seed for 8 to 9 months provided the seed is of reasonably good quality when placed in storage (Fig. 12).

One alternative to air-conditioned storage of soybean seed in subtropical and tropical areas is to condition the seed to about 9 percent moisture and then package it in moisture-vapor-proof packages such as 10 mil thick polyethylene bags. The plastic bags should be heat-sealed and precautions should be taken to prevent puncturing. Considering the long-term economics of soybean seed storage and the effectiveness of the two systems, i.e., air-conditioning or moisture-vapor-proof packaging, air-conditioning is the preferred method.

Soybean seed storage problems can also be lessened in subtropical and tropical areas by concentrating seed production in the "minor" rainy season or in the dry season under irrigation. Seed yield may be less but the storage period will be reduced from 8 to 9 months to 2 to 3 months. Air-conditioned storage usually is not necessary for 2 to 3 months' storage provided the seed is dried to 13 percent moisture or less.

For long-term maintenance (5 to 8 yrs) of valuable seed material such as genetic lines, cultivar collections, limited quantities of breeder seed, and the like, a highly conditioned storeroom is essential. The storeroom should be well constructed so that transmission of moisture-vapor through the walls is minimal. It should be insulated and equipped with a refrigeration-dehumidification system capable of maintaining conditions of about 10°C and 50 percent relative humidity (Fig. 13).
Fig. 12. "Air-conditioned" seed storage facilities designed for the Government of Honduras. Conditions of about 23°C and 55 percent relative humidity are maintained in the storerooms with conventional air-conditioning units and condensation-type dehumidifiers.
Fig. 13. Details of construction, insulation, and moisture-vapor proofing of cold storage room for long-term storage of seed. Cooling and dehumidification are best accomplished with a refrigeration system of adequate capacity combined with a desiccant dehumidifier.
Evaluation of Seed Quality

The quality of soybean seed is routinely evaluated by standard test procedures (8). These procedures include a purity analysis, germination test, and usually a moisture test.

**Purity analysis.** In the purity analysis the percentage by weight of pure seed, other crop seed (including seed of other varieties as can be identified), weed seed, and inert matter is determined. Modern soybean varieties can seldom be positively identified by seed characters alone. Often, however, it is possible to determine that a particular seed is not of the variety specified. Although various seed and seedling characters are useful in determining trueness-to-cultivar in soybeans, field grow-out tests generally are necessary to accurately assess cultivar purity.

**Germination test.** The percentage by number of seeds capable of producing "normal" seedlings is determined. The germination test has serious limitations as a measure of the stand and crop producing potential of soybean seed, as will be discussed below.

**Moisture test.** The moisture content of the seed, wet weight basis, is determined, usually with an electric moisture meter. Moisture content data are very important from harvest through marketing.

**Germination, Deterioration, and Vigor**

The stand and plant producing potential of soybean seed, and other kinds of seed as well, is most commonly evaluated by a germination test. Exacting procedures for determining the germination percentage of seed lots have been developed and perfected over the past 100 years and are codified in the Rules for Testing Seed (8). In many ways, the standard germination test appears to admirably serve the needs and interests of seed analysts, seed control officials, and seed producers. The germination test, however, has several deficiencies which should be recognized. The deficiencies of the germination test as a measure of the plant producing potential of seed stem from two main sources: the overall philosophy of germination testing, and the nature of seed deterioration.

Procedures for germination testing of seed have been established on the basis of the "optimization" principle, i.e., test conditions are optimized so that maximum germination percentages are obtained. Thus, germination tests are made largely on "artificial," standardized, essentially sterile media, in humidified, temperature controlled germinators for periods sufficiently long to permit even the weakest seed to make its debut as a normal seedling.

It has not been well established that the performance potential of a seed is progressively impaired through deteriorative processes that inevitably occur over time--a few minutes or many years. The identity and sequence of the deteriorative changes--or the manifestations of change--that occur in a seed as it dies are known only in a general way. The available evidence, however, suggests that during deterioration essential biological systems and mechanisms are progressively impaired so that the consequences, in terms of germination and subsequent growth and development, become progressively more serious (4, 17, 21, 29, 30, 38, 53).

Membrane degradation and loss of permeability control occur at an early stage during seed deterioration (1, 14, 21). Energy yielding and biosynthetic processes are then impaired with a resulting decrease in rates of respiration, transfer of dry matter from supporting tissues to the embryonic axis, germination, and early seedling growth (21, 29, 38, 58, 59). At about this stage in the progress of deterioration, the seed appears to lose much of its natural resistance to environmental stresses and seed rotting microorganisms.

Reduced rate of germination and early seedling growth are subsequently reflected in a decreased rate of plant growth, delayed flowering and maturity, and reduced yield. As deterioration progresses further, the seed fails to emerge from the seed bed even under rather favorable conditions. Finally, it loses its capacity to "germinate" even in the optimum environment of the germinator. Because the seeds within a lot are not uniform in physiological quality and they become progressively more so as deterioration advances, irregular and non-uniform emergence, plant growth, development, and maturation are other important consequences of deterioration that precede the 0 percent germination stage.

The germination test is an insensitive and misleading measure of seed quality because it focuses primarily on the final, albeit most disastrous, consequences of deterioration, and does not adequately take into account the very substantial loss in
performance potential that can and does occur before the germinative capacity is lost. Yet, the lesser consequences of seed deterioration, such as reduced resistance to environmental stresses, decreased seedling and plant growth rate, and so on, have become of greatest importance. Few seedsmen knowingly sell, and few farmers will knowingly plant, dead or low germination seed. Both seedsmen and farmers, however, are damaged all too frequently because seed of "good" germination fails to perform satisfactorily when planted in the field. Seed that germinates moderately well but has low stand establishment potential is said to be low in vigor.

Many attempts have been made to rigorously define the term vigor as applied to seed. The result is a multitude of concepts and definitions all of which have some degree of validity and applicability, and which collectively cover the subject rather thoroughly (23, 38, 40, 50, 51, 59). While space does not permit examination of the various definitions and concepts of seed vigor, it should be pointed out that vigor, as an attribute of quality, is meaningful only in reference to germinable seed. A nongerminable seed has zero performance potential, hence, no vigor. Vigor tests, therefore, supplement the standard germination test. The germination test establishes the percentage of germinable seed in a population or lot, while a vigor test evaluates the performance potential of the germinable seed. Vigor tests, of course, also assay the extent of deterioration of seeds within a population which really determines their performance potential. Thus, vigor and degree of deterioration are essentially the positive and negative aspects, respectively, of performance potential.

A variety of vigor tests have been developed but only a few have found application in a more or less routine manner in seed quality evaluation and control programs (23, 38, 40, 50, 59). The more successful vigor tests evaluate response-reactions of individual seed which permits expression of test results as a percentage by number of seeds tested, much as in the germination test.

Byrd and Delouche (13, 14) compared the efficiency of several of the more widely used vigor tests with the germination test for evaluating the progress of deterioration during storage and the field emergence potential of soybean seed. They found that germination percentage was the least sensitive index of the progress of deterioration and reduction in emergence potential during storage (Fig. 14). Soybean seed stored in an environmentally controlled room at 30°C and 50 percent relative humidity did not significantly decrease in germination percentage until after 7 months. Accelerated aging and cold test responses, however, significantly decreased after 1 to 4 months' storage, as also did field emergence percentage.

Preliminary results from extensive studies being conducted by Andrews and Vaughan (5) with the objective of establishing a vigor rating system for soybean seed lots indicate that two vigor tests are especially promising for soybeans: the accelerated aging test, and the tetrazolium test interpreted for vigor.

Accelerated aging test. The accelerated aging test was developed for evaluating the storability of seed lots (21). Everson (26) and associates at the Iowa State University Seed Testing Laboratory have effectively used the test to determine the "carry-over" potential of soybean seed lots. For this purpose they used accelerated aging conditions of 40°C and 99 percent relative humidity for 30 h followed by a 7 day regular germination test.

It is not surprising that the accelerated aging test also has proven useful as a vigor test for evaluating the stand producing potential of seed. Storability, after all, is influenced by vigor or degree of deterioration just as is rate and percentage of emergence. In regard to soybean seed lots, accelerated aging under conditions of 40°C and 100 percent relative humidity for 48 h or for 72 h followed by regular germination test have produced results that correlate closely with field emergence.

Tetrazolium test. The tetrazolium test (TZ) is most widely used to rapidly estimate the germination percentage of seed lots. Procedures for use of the TZ test in this manner have been developed and published (25, 51). The TZ test is equally applicable for evaluating vigor of seed as has long been advocated by Moore (47, 48). When conducted by an experienced analyst, it is probably the most informative of all tests for evaluating the physiological quality of seed.

We use the classification system developed by Moore. Category 1 represents the most vigorous seed, category 2 the second most vigorous, and so on, through category 5 which represents the least vigorous of the germinable seed. Categories 6, 7, and 8, which encompass nongerminable seed, are usually not used in establishing a vigor rating but do provide useful
information regarding the progress of deterioration in the lot. The numbers of seed falling into categories 1 and 2, or 1, 2, and 3, are variously used to compute a germination or tetrazolium "energy" percentage, i.e., percentage of vigorous seed.

Fig. 14. Response-reactions of Lee 68 soybean seed during storage at 30°C and 50 percent relative humidity, relative to levels of responses at the beginning of storage, i.e., 0 months = 100 percent.

In our view, quality control programs for soybean seed should utilize at least one vigor test in addition to the regular germination test to assess seed quality. And, these should be conducted at least twice with the last test as close to the end of the storage period as possible.

SUMMARY

An effective, efficient seed production and supply system is necessary for extension of soybean production in all countries.

The most chronic seed quality problems in soybeans relate to germinability and vigor. Soybean seed is inherently short-lived and structurally weak as compared to other kinds of seed. Substantial losses in germinability and vigor are caused by hot, dry weather during seed maturation, weathering from rainfall, and warm temperatures during the harvest period, and mechanical abuse during harvesting and handling operations. Production of high quality soybean seed requires timely harvest followed by aeration or drying, or both, as necessary to reduce seed moisture content to 13 percent or less in temperate areas, and 12 percent or less in subtropical and tropical areas, and careful combining and handling to minimize mechanical damage.

In subtropical and tropical areas soybean seed should be stored in an air-conditioned storehouse with conditions of 20° to 22°C or less and 60 percent relative humidity or less, to maintain quality from harvest to planting.

Germination percentage is not always a reliable index of the stand and crop producing potential of soybean seed. Seed lots of good germination but low in vigor can and do perform poorly in the field even under rather favorable conditions. Therefore, use of vigor tests to supplement information provided by the germination test is recommended.
REFERENCES


