Earlier harvest and drying of soybean seed within intact pods maintains seed quality

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Earlier harvest and drying of soybean seed within intact pods maintains seed quality

by

Ross David Ennen

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Crop Production and Physiology (Seed Science)

Program of Study Committee:
Russell Mullen, Co-major Professor
A. Susana Goggi, Co-major Professor
Kenneth Moore

Iowa State University
Ames, Iowa
2011
# TABLE OF CONTENTS

## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## CHAPTER 1. GENERAL INTRODUCTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Thesis Organization</td>
<td>2</td>
</tr>
<tr>
<td>Literature Review</td>
<td>3</td>
</tr>
<tr>
<td>References</td>
<td>26</td>
</tr>
</tbody>
</table>

## CHAPTER 2. EARLIER HARVEST AND DRYING OF SOYBEAN SEED WITHIN INTACT PODS MAINTAINS SEED QUALITY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>33</td>
</tr>
<tr>
<td>Introduction</td>
<td>34</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>36</td>
</tr>
<tr>
<td>Results</td>
<td>39</td>
</tr>
<tr>
<td>Discussion</td>
<td>43</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>46</td>
</tr>
<tr>
<td>References</td>
<td>46</td>
</tr>
</tbody>
</table>

## CHAPTER 3. GENERAL CONCLUSIONS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Discussion</td>
<td>56</td>
</tr>
<tr>
<td>Recommendations for Future Research</td>
<td>56</td>
</tr>
<tr>
<td>References</td>
<td>59</td>
</tr>
</tbody>
</table>

## APPENDIX. ADDITIONAL FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

## ACKNOWLEDGMENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>62</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. Average initial moisture content (wet-weight basis) and seed dry weight for all soybean varieties by pod maturity stage and year ...................... 50

Table 2. Analysis of variance (ANOVA) of the standard germination test, accelerated aging test, and electrical conductivity of seed leachate for soybean seeds harvested at three pod maturity stages (full-size green, yellow, and brown) and exposed to two drying treatments (podded or depodded) at three temperatures (27°C ± 2, 31°C ± 2, or 41°C ± 2) ......................................... 51

Table 3. Percentage of normal seedlings in standard germination and accelerated aging tests for soybean seeds harvested at three maturity stages and exposed to two drying treatments at three drying temperatures in 2009. Electrical conductivity of seed leachate (µS cm⁻¹ g⁻¹) also shown.................. 52

Table 4. Percentage of normal seedlings in standard germination and accelerated aging tests for soybean seeds harvested at three maturity stages and exposed to two drying treatments at three drying temperatures in 2010. Electrical conductivity of seed leachate (µS cm⁻¹ g⁻¹) also shown.................. 54
CHAPTER 1. GENERAL INTRODUCTION

Introduction

The increased importance of soybean seed quality can be credited to the continued emphasis on early planting. Soybean breeding programs spend a great deal of time and money to breed seed that emerges rapidly and uniformly from cool, wet soils. Since 2000, the price of transgenic soybean seed has increased at a rate of over $3/bu/y. The average price of transgenic soybean seed, as of 2010, was $53/bu of seed (USDA-NASS, 2010). In order to receive the most return on investment, soybean seed producers constantly look for ways to increase or maintain seed quality while minimizing field losses.

Soybean seed development and maturation has been linked to various physiological and biochemical processes. It has been widely understood that most seeds reach their greatest potential seed quality at physiological maturity (Harrington, 1972; Miles et al., 1988), or maximum accumulation of seed dry matter. However, soybean seeds destined for seed are mechanically harvested at similar developmental stages as soybeans grown for grain production. Physiological maturity occurs in soybean seed at high seed moisture content, which precludes harvest by conventional means. The seed corn industry has resolved this issue by harvesting the entire ear of corn near physiological maturity and conditioning/sorting the seed in a controlled environment (seed conditioning plant). This allows corn seed producers to minimize risks of physiological seed deterioration due to field losses, an early frost, and weathering. The corn seed industry’s approach of early harvesting of corn ears and conditioning seeds in controlled environments may be applicable to soybean seed production.

Soybean seeds are inherently more susceptible to mechanical damage than corn seeds, especially at high seed moisture contents. Harvesting high-moisture soybean seeds and then
drying is more difficult to do than corn seeds because of differences in their intrinsic qualities. Oily seeds, such as soybeans, are more prone to lipid peroxidation, especially when stored at high temperature and relative humidity (Stewart and Bewley, 1980). One way to minimize the negative effects of harvesting high moisture soybeans may be to harvest and dry the seeds within intact pods. Samarah et al. (2009) found that harvesting and drying soybeans within intact pods helped maintain soybean seed quality (viability and vigor); however, the range of drying temperature and varietal differences were limiting. In order to elucidate these effects, three objectives were established to determine: (1) the pod harvest stage at which soybean seed quality be harvested and maintained when soybean seeds are dried within intact pods, (2) the drying temperature at which the soybean pod has little effect on soybean seed quality, (3) the pod maturity stage in which the effect of the soybean pod no longer affects seed quality during dry down.

**Thesis Organization**

One journal paper titled “Earlier harvest and drying of soybean seeds in intact pods maintains seed quality” will be submitted for publication and has been included as the second chapter in this thesis. A general conclusions (Chapter 3) section is followed by additional tables (appendix A) and acknowledgments.
Literature Review

Physiological Maturity

Physiological maturity (PM) of seed is considered to occur when seed has accumulated its maximum dry weight (Shaw and Loomis, 1950; Harrington, 1972). Miles et al. (1988) described PM as maximum accumulation of seed dry weight and complete transition from green to yellow color. The percent moisture (wet-weight basis) of soybean \([Glycine\ max\ (L.\)\ Merr]\) seed at maximum dry weight is variable, ranging from 50-62% (Howell et al., 1959; Crookston and Hill, 1978; Tekrony et al., 1979; Samarah et al., 2009). There have been multiple attempts to describe PM of soybeans and the developmental stage when it occurs. These studies attempted to determine PM by correlating it with qualitative characteristics. Fehr et al. (1971) determined that PM in soybeans was reached at the reproductive development stage R7, described as “pods yellowing” and “50% of leaves yellow.” A study conducted by Tekrony et al. (1979) concluded that one mature pod on the main stem was an acceptable indicator of PM and found that seed moisture at PM ranged from 54-62% in soybeans. In the past, a common method for determination of PM of a single seed was to describe the seed as completely yellow, which was not useful for the determination of PM of the whole plant. TeKrony et al. (1981) studied the usefulness of several visual indicators of PM determination, and concluded that results from their previous research (1979) proved to be a useful indicator in the determination of PM for a single plant or field population of soybeans. Change of color in the soybean hilum was found to characterize PM (Tekrony et al., 1979), similar to the presence of an abscission layer (black layer) in corn. Crookston and Hill (1978) determined that loss of green color from pods may be a useful tool for prompt determination of PM. The authors concluded that seed shrinkage may
also be a useful indicator of PM in soybeans because seed shrinkage occurred immediately following loss of green color in seeds (Crookston and Hill, 1978).

**Seed Development and Quality**

Seeds produced by sexual fusion typically undergo three developmental stages during seed formation. The first stage (80% of growth) is characterized by rapid cell division and elongation, which allows for large increases in seed weight. The second stage is characterized by the dissolution of nutrient supply via the funiculus. The seed will no longer accumulate photosynthates (weight) from the mother plant. The third seed growth stage occurs when seed undergoes further desiccation and can be influenced by a variety of environmental or pathogenic stresses (Copeland and McDonald, 2001).

Early research performed by Harrington (1972) suggested that developing seeds reach their greatest seed quality at PM, defined by Shaw and Loomis (1950) as maximum accumulation of seed dry weight. This hypothesis has been widely accepted for use in multiple crops, including soybeans (Delouche, 1980; Miles et al., 1988). However, a more recent study of seed quality during barley and wheat development concludes that the term PM is misleading and should not be used to describe maximum seed quality (Ellis and Filho, 1992). Ellis and Filho (1992) found that maximum potential seed longevity occurred after PM, between 3 and 21 d. These results refuted Harrington’s hypothesis (1972) that maximum seed quality is attained at PM. Siddique and Wright (1994) also found that maximum seed quality of peas (*Pisum sativum* L.) was not achieved at PM, and that pea seed deterioration did not begin until after physiological maturity. Even with evidence against Harrington’s hypothesis (1972), the
assumption of maximum seed quality occurring at physiological maturity is still widely accepted by seed physiologists.

Soybean seeds must endure many physiological and biochemical changes during development and maturation which is essential for germination of the seed (Miles et al., 1988). Miles et al. (1988) investigated many characteristics of freshly harvested soybean seed to determine when fresh (non-desiccated) seeds attain the ability to germinate. Fresh soybean seeds were then evaluated for seed moisture, dry seed weight, germination and respiration (Miles et al., 1988). The researchers harvested pods at four developmental stages: full seed, mid-pod fill, expanded pod, and yellow pod. Harvest of pods was based visually on the area of the locular cavity occupied by the seed as well as pod color (Miles, et al., 1988). The authors found that near maximum viability (radicle protrusion) occurred at only 35% seed dry weight accumulation, but maximum germination (development of normal seedlings) did not occur until PM, or maximum seed dry weight accumulation (Miles et al., 1988). Obendorf et al. (1980) found that immature soybean seeds, harvested at less than 34 days after flowering (DAF), obtained the ability to germinate before maximum seed dry weight was reached. Seeds harvested at less than one-half their full size have very little potential to withstand desiccation (Obendorf et al, 1980).

In the late 1960s, soybean seed producers showed interest in premature defoliation of soybean seed fields in order to facilitate earlier dry-down and harvest. In response, Burris (1973) initiated a study on the effects of seed maturation on soybean seed quality. The author found that seed weight increased linearly until 50 DAF. All cultivars had increased germination as DAF increased, except for two cultivars between 30 and 40 DAF. This reduction in germination between 30 and 40 DAF was attributed to an increase in hard seed (impermeable) percentage (Burris, 1973). Studies performed by Hanway and Weber (1971) and Egli (1975) studied rate of
dry matter accumulation in soybean seed. Hanway and Weber (1971) found that although dry matter accumulation varied at the individual plant level, dry matter accumulation of seed remained consistent at 99 kg ha\(^{-1}\) day\(^{-1}\) from full bloom stage to stage 10 (40% of full leaf weight). It was noted that rapid dry matter accumulation occurred at different stages after full bloom between varieties, but dry matter accumulation rate remained constant within varieties during both study years (Hanway and Weber, 1971). A study that evaluated associations between grain yield and growth rates of individual soybean seed found no connection between the two (Egli, 1975). It was concluded that rate of dry weight accumulation was not significantly related to grain yield; however, soybean grain yield was closely related to seed number across both study years (Egli, 1975).

Accumulation of seed mass ceases once a seed is harvested from a plant, seed viability changes still occurred when seeds are harvested at different developmental stages (Burris, 1973). As found by Burris (1973), soybean seeds can remain viable when harvested at an immature developmental stage. Any physiological changes that occur after seed development (PM) must be due to the seed maturation process. In 1981, (Adams and Rinne) demonstrated this fact by finding that freshly harvested (immature) soybean seeds were not viable when dried; however, immature seeds dried within intact pods matured into viable seeds and produced healthy plants. Soybean seeds harvested as early as 26 DAF were viable when allowed to air-dry within intact pods (Adams et al., 1983). Allowing immature, podded soybean seeds to air-dry imposed the maturation process by terminating seed expansion, maintaining enzyme activities (leucine aminopeptidase, \(\alpha\)-galactosidase, and aspartate aminotransferase), and modifying soluble proteins (Adams and Rinne, 1981). Soybean seeds dried within intact pods showed a much slower rate of moisture loss than seeds dried with pods removed. Seed weight was not
significantly influenced by either drying seeds within or without pods (Adams et al., 1983).

Much of the time allocated to seed development is used for increasing seed mass, which is not essential for viable seed production. However, it may be important in terms of ecological advantage (Adams and Rinne, 1981) or seed vigor. Adams and Rinne (1981) concluded that soybean seed maturation is independent of the parent plant, but is necessary for production of viable seeds.

Changes in Soybean Seed Constituents during Maturation and Seedling Growth

A series of studies performed by Rosenberg and Rinne (1986; 1987; 1988; 1989) focused on intrinsic changes that occur within soybean seeds during natural and precocious maturation. It is widely accepted that immature (high moisture) seeds will not germinate unless subjected to an artificial drying treatment (Burris, 1973; Adams and Rinne, 1981; Adams et al., 1983). Rosenberg and Rinne (1986) studied this phenomenon by examining the process that initiates seed maturation and observed how moisture loss initiates production of polypeptides that are related to this occurrence. It was also of author interest to determine the earliest point at which seeds can be harvested and still exhibit germination without the influence of artificial drying (Rosenberg and Rinne, 1986). To answer this question, soybean seeds were rated on their ability to germinate and establish growth as a seedling. It is important to note that their germination and seedling growth evaluation criteria are different from AOSA rules (2003). Seed germination was evaluated alongside seedling growth, in which germination was described as radicle protrusion (< 2 cm) and seedling growth was described as “the appearance of a radicle greater than 2.0 cm in length and with secondary roots where the hypocotyl also showed growth” (Rosenberg and Rinne, 1986). Fresh (non-desiccated) soybean seeds harvested between 35 and 45 DAF (35 and
140 mg seed\(^{-1}\) dry weight, respectively) exhibited less than 40% rolled-towel germination and zero seedling growth. It is safe to assume these seeds did not transition from germination to seedling growth (Rosenberg and Rinne, 1986). Transition from germination to seedling growth did not occur until after 63 DAF (91% for both rolled-towel germination and seedling growth), at which seed moisture was less than 55%. It was at a similar stage in growth (54 DAF) at which Adams et al. (1983) first detected two glyoxolate cycle enzymes during seed imbibition, isocitrate lyase and malate synthase. The glyoxolate cycle allows seeds to use lipids (triglycerides) as an energy source during germination (Hopkins and Huner, 2004). Prior to 54 DAF, isocitrate lyase and malate synthase were not detected during imbibition of soybean seeds. Conversely, when artificially air-drying immature seeds (33 DAF), isocitrate lyase and malate synthase levels were detected in imbibing seeds at similar activity levels as naturally matured and rehydrated seed (Adams et al., 1983). From these results, Rosenberg and Rinne (1986) suggested a link between the appearance of these glyoxolate cycle enzymes and the ability of germinated (radicle protrusion) seed to establish seedling growth.

Past research has also focused on the changes in soybean seed constituents during germination and seedling growth of natural and precocious matured seeds. Rosenberg and Rinne (1987) focused on carbohydrate, protein, and oil concentration. Soybean seeds were harvested at 35 DAF and 70 DAF in order to represent precociously and naturally matured seeds, respectively. To induce precocious maturation, immature seeds (35 DAF) were dried within intact pods at 24°C and 58% RH for 0, 1, 3, 5, or 7 days. During seven days of precocious maturation, starch content declined and soluble sugar levels increased, similar to starch and sugar contents of seed undergoing natural maturation processes (Rosenberg and Rinne, 1987). Naturally matured seed (70 DAF) had 57% more dry weight than precociously matured 7 d pod-
dried seeds; however, proportions of seed constituents were similar to seeds that matured naturally. Starch, soluble sugar, protein, and oil levels during germination and seedling growth of precociously matured seeds followed patterns similar to naturally matured seeds (Rosenberg and Rinne, 1987). Further studies by Rosenberg and Rinne (1988; 1989) focused on protein synthesis during natural and precocious maturation in soybean seeds.

It has been shown by previous studies that the process of soybean seed maturation can be imposed through precocious maturation (Rosenberg and Rinne, 1986; Rosenberg and Rinne, 1987). Therefore, physiological and biochemical processes associated with seed maturation can be separated from processes related to seed development (Rosenberg and Rinne, 1986). The objective of a study performed by Rosenberg and Rinne (1988) was to compare levels of protein synthesis during natural and precocious maturation. Total soluble proteins and methionine-labeled proteins were extracted from control seeds, developing seeds, precociously matured seeds, and naturally matured seeds (Rosenberg and Rinne, 1988). Several polypeptides were found in naturally and precociously matured seed and were described as “mature polypeptides.” In vitro translation experiments showed these mature polypeptides were found during natural and precocious maturation, but not in control seeds (35 DAF). The authors speculate that the presence of the mature polypeptides may initiate the ability of matured soybean seed to begin seedling growth (Rosenberg and Rinne, 1988).

A 1989 study (Rosenberg and Rinne) looked at the temporal relationship between synthesis and metabolism of polypeptides in naturally and precociously matured soybean seeds relative to seed-rehydration, germination, and seedling growth. Three of the maturation polypeptides that accumulated during maturation continued production during early stages of rehydration and germination (5-30 h after imbibition). Synthesis of these polypeptides ceased
during the transition from germination to seedling growth (30-72 h after imbibition). The termination of mature polypeptide synthesis was marked by hydrolysis of storage polypeptides that had been created during seed development (Rosenberg and Rinne, 1989). The authors propose that this represents a major metabolic difference between precociously and naturally matured seeds. If soybean seeds are not given enough time to mature on the plant before being precociously matured, seeds will cease accumulation of storage protein reserves (Rosenberg and Rinne, 1989).

Factors Influencing Soybean Seed Quality

Following PM, soybean seeds continue to undergo maturation drying until harvest maturity, the moisture content at which seeds can be threshed with mechanical harvesters (Delouche, 1980). During the time between PM and harvest maturity, field weathering may cause negative effects on the viability and vigor of soybean seed (TeKrony et al., 1980). Many variables can affect soybean seed before it reaches a harvestable moisture content (<15%). In tropical geographic regions, rapid seed deterioration limits soybean seed quality due to delayed harvest under high ambient temperature and relative humidity. Nangju (1977) found that a harvest delay of 21 d decreased soybean seed quality under lowland tropical areas, where as TeKrony et al. (1980) detected a loss in soybean vigor after nearly 40 days. Howell et al. (1959) determined respiration rates in developing soybeans at different moisture contents, and compared the results to leachates collected under plants growing in the field and greenhouse. Respiration rates of developing soybean seeds were positively correlated to stage of seed development and moisture content. Green seeds nearing PM were found to have the highest respiration rate (69.1 μL h⁻¹ seed⁻¹). Drastic reduction in respiration (12.9 μL h⁻¹ seed⁻¹) did not occur until seeds were
near a 30% moisture content from brown pods (Howell et al., 1959). Temperature affected seed respiration, but not to the extent of seed moisture content (Howell et al., 1959). Amable and Obendorf (1986) simulated preharvest seed deterioration by inducing water content fluctuations in soybean seed for 30 d. Seed deteriorated most rapidly under high water content regimes at high temperatures and were non-viable at 20 days. Low rates of oxygen uptake during seed imbibition were correlated with increased seed deterioration (Amable and Obendorf, 1986).

The soybean seeds exposure to alternate wetting and drying PM results in reduced seed quality. Allowing seeds to remain in pods past harvest maturity may have negative effects on seed imbibition. Krul (1978) showed that soybean pods contained unknown substances that blocked imbibition of water by seeds; pods that were rehydrated before harvest showed increases of these diffusible substances. Moist seeds are naturally protected against variations in atmospheric moisture because embryo and seed coat cells remain turgid during late development and early maturation (Moore, 1971). Severe seed deterioration occurred when dry seed became exposed to alternating events of rain or even dew. Seeds exposed to variable weather and storage conditions revealed that reduction in viability was mainly seed coat related and caused by rapid absorption of water by localized tissues. The natural protective mechanism of the seed coat deteriorates with the alternate wetting and drying of seed coat cells (cuticular, palisade, column, and parenchyma layers) (Moore, 1971).

The period from PM to harvest maturity may fluctuate from a few days to several weeks, depending on the cultivar and field environment. TeKrony et al. (1980) found that seed viability remained high (>80%) from PM to harvest maturity in all but one location. However, vigor of seed extracted past harvest maturity decreased significantly. Also, vigor of these seeds reached a level less than 50% germination outside one month of harvest maturity. Air temperature, relative
humidity, and precipitation were closely related to seed vigor loss while seeds remained in the field following harvest maturity. A physiological and chemical study on low- and high-vigor soybean seeds found that following imbibition, high-vigor seeds were better able to mobilize energy reserves to utilizable metabolites (Wahab and Burris, 1971). Decreases in seed vigor due to field weathering emphasizes the importance of well-timed harvest of soybean seed fields (TeKrony et al., 1980). Further evidence for timely seed harvest was established by TeKrony et al. (1984) in a study that tested the effect of harvest date on Phomopsis sp. seed infection. The study concluded that date of harvest maturity strongly influenced Phomopsis sp. seed infection of all cultivars tested. A four-year regression analysis indicated that 70% seed infection resulted in 40% germination of soybean seeds (TeKrony et al., 1984).

Many times, production of high quality soybean seed is a challenge due to delays in harvesting from unexpected weather events. These harvest delays increased seed deterioration due to plant lodging or field losses due to shattering (Philbrook and Oplinger, 1989). In areas such as Kansas, drier weather during harvest can produce dry, fragile seed that may be easily damaged during seed conditioning. Schaffer and Vanderlip (1999) found that soybean seed germination was reduced in seeds that had been conditioned (cleaned) at moisture contents less than 10%. Mechanical harvest can also have a compounding effect on low moisture soybean seed. Costa et al. (2001) found that levels of breakage and seed coat rupture from mechanical harvesting were increased in seed lots already damaged by field weathering.

**Desiccation Tolerance**

Many plant species found in temperate climates are orthodox by nature, meaning they have the ability to survive desiccation and prolonged storage under favorable temperature and
humidity. This physiological phenomenon is called desiccation tolerance, where orthodox seeds are able to dry to moistures far beyond physiological maturity while maintaining viability. The ability to desiccate (while maintaining viability) has not been found in recalcitrant seeds. Recalcitrant seeds are those of tropical species, are shed from plants at high moisture contents, and are typically sensitive to drying (Farrant and Walters, 1998).

The ability of orthodox seeds to survive periods of prolonged storage is ecologically important in wild species and commercially important in cultivated species. Seeds dispersed from a wild species in temperate regions may not have the available soil moisture required for seed imbibition and germination; they are able to remain viable until that moisture becomes available. The ability of commercially cultivated seeds to undergo desiccation is also important in terms of safe seed storage and handling.

The capacity for seeds to survive harvest and rapid desiccation does not become present until late stages of seed development. When allowed to fully mature on the plant (maturation drying), soybean seeds reach the ability to germinate during early developmental stages, but seeds must undergo further development if they are to remain viable during rapid desiccation (Ellis et al., 1987). Work done with castor beans has shown that seeds achieved tolerance to slow desiccation earlier in seed development than tolerance to rapid drying (Kermode and Bewley, 1985). However, it may be argued that the slow rate of drying simulated maturation drying (Ellis et al., 1987). Ellis et al. (1987) looked at the relationship between seed quality and the development of desiccation tolerance in six grain legumes, including soybeans. The goal was to determine the moisture content of the seed during the acquisition of desiccation tolerance, and to determine if field-grown grain legumes should be harvested prematurely (Ellis et al., 1987). In soybeans, acquisition of desiccation tolerance coincided with PM (maximum dry weight);
however, harvesting and rapidly drying seeds at PM did not result in maximum seed quality. Maximum seed quality did not occur until soybean seeds were at roughly 45% moisture content (Ellis et al., 1987). This finding refuted Harrington’s hypothesis (1972) that maximum seed quality occurs at PM; however, other evidence against Harrington’s hypothesis does exist (Ellis and Filho, 1992; Siddique and Wright, 2003). It was also found that delaying soybean seed harvest beyond optimal moisture had a detrimental effect on seed viability and percentage of seedling abnormalities (Ellis et al., 1987).

Desiccation tolerance varies among seed varieties due to differences in embryological development of the parent plant (Farrant and Walters, 1998). The ability of seeds to acquire desiccation tolerance has been credited to four attributes reviewed by Farrant and Walters (1998). These include: the accumulation of protectant sugars and the loss of reducing sugars, the ability to express late embryogenesis abundant proteins (LEA), the limitation of vacuolation in embryonic tissues, and the ability to stop or reduce metabolism (Farrant and Walters, 1998).

Research in the mechanisms of desiccation tolerance in soybeans (*Glycine max*) is not as prevalent as in maize (*Zea mays*). However, Blackman et al. (1991; 1992) focused on the role of sugar and protein regarding desiccation tolerance of developing soybean seeds. As in maize, LEA proteins are hypothesized to comprise a role in the protection of desiccation injury in soybeans. A potential correlation between LEA protein presence and the desiccation tolerant state of soybeans was tested. LEA proteins were measured from proteins that showed similar temporal expression and were resistant to heat coagulation. Measurements were conducted in developing seed and in germinating seed. The authors found that enough LEA proteins had accumulated at 44 DAF to acquire desiccation tolerance and that desiccation tolerance was lost after 18 hours of water imbibition (Blackman et al., 1991). More importantly, seeds exhibited
premature acquisition of desiccation tolerance when seeds were extracted and dried slowly (Blackman et al., 1991). This finding showed that soybean seeds may undergo slowed desiccation before or at physiological maturity while maintaining germinability. It provides further evidence that seed quality in soybean seeds can be improved or maintained by controlled slow drying of high moisture seed.

The scope of this research widened when Blackman et al. (1992) found that desiccation tolerance was induced in immature seeds (34 DAF) by slow drying. Identification of important sugars involved in acquisition of desiccation tolerance was performed. Sugars identified during a slow drying treatment and high relative humidity control treatments were: sucrose, raffinose, stachyose, and galactinol. Stachyose and raffinose were found to significantly increase under slow drying, but did not show significant increase under high relative humidity. Stachyose content was more than double the content of raffinose. Under slow drying, sucrose decreased rapidly during the first day of desiccation. In ensuing days, sucrose content slowly increased to an amount five times greater than sucrose content measured in the high relative humidity treatment. The authors concluded that the high sucrose level was associated with desiccation tolerance under slow drying conditions, however, sucrose was not the single determining factor in desiccation tolerance. Under high relative humidity, galactinol was the only saccharide that increased in accumulation. Soluble sugars other than stachyose and sucrose were only a small proportion of the sugars measured. These sugars (raffinose and galactinol) did not differ significantly between slow-dried seeds and seeds held under high relative humidity. From this, it was presumed that only stachyose and sucrose have any role in the development of desiccation tolerance in slow-dried seeds (Blackman et al., 1992). Acquisition of desiccation tolerance plays
a crucial role in the potential quality of soybean seed and is a factor that should be considered when attempting to harvest and dry soybean seeds near PM.

**Soybean Seed Drying**

In soybean, PM is reached at the point of highest dry matter accumulation. Soybean moisture percentage at this stage can range from 50-62\% (Howell et al., 1959; Crookston and Hill, 1978; Tekrony et al., 1979; Samarah et al., 2009), which is unsuitable for conventional mechanical harvest. Seeds allowed to mature naturally in the field can be subjected to potentially unfavorable field conditions (TeKrony et al., 1980). These unfavorable conditions are especially severe in tropical and sub-topical areas, where temperature and humidity play an important role in seed degradation. In which case, drying soybean seeds could be one of the most critical steps in maintaining seed quality, especially when harvesting at high seed moisture content. An established rule in seed drying is a water removal rate of 0.3\% per hour at high temperature (43°C) and a flow rate of 5.5 m³ minute⁻¹ ton⁻¹ (Brandenburg et al., 1961).

Kryzanowski et al. (2006) used a prototype drier that had the feature of removing moisture out of the air before it was heated and passed through the seed. Their intent was to study the effects on seed quality by drying soybean seed using ambient air temperature at low relative humidity (RH). Through experiments with the prototype dryer, it was found that seed quality was maintained by drying high moisture seeds (22\%) with an average temperature of 34°C and a RH of 24.6\% with a 9 cm-high seed layer. A second experiment was conducted that attempted to dry a thicker seed layer (50 cm-high) and similar results were found with 22\% moisture content seeds (Kryzanowski et al., 2006).
A large-scale study by Levien et al. (2008) focused on drying soybean seed using drying air of different relative humidities within a stationary dryer. In large-scale seed production operations, timing may be important. Thus, in order to hasten drying time and free dryer capacity, seed producers may be tempted to use high temperatures and high air flow rates in stationary dryers (Levien et al., 2008). In cereal grain drying, temperatures in the range of 32 and 43°C are considered maximum values, because temperatures above 43°C are likely to incur physical and chemical damage to seeds (Brooker et al., 1974). Seeds dried with high heat and air flow are likely to remain warm and dry during the final stages of a drying operation, in which case they are more fragile and susceptible to mechanical damage. Levien et al. (2008) theorized that increasing relative humidity at the last stages of soybean drying could reduce fragility and lower the seed moisture content gradient within the dryer. They found that increasing the RH by 15 percentage points (30 to 40% RH) decreased the seed moisture gradient below 2% (within the stationary dryer) and reduced the drying rate by about 20%. Soybean seed quality (accelerated aging, tetrazolium, and field emergence) was not affected by the high relative humidity treatment toward the end stages of seed drying (Levien et al., 2008). Chirmaksorn (1978) studied the effects of high temperature drying on soybean seed germination. Temperature treatments ranged from 38 to 76°C. Results showed that it was possible to dry soybeans at 54°C for 3 h if seeds were moving continuously. However, only two low seed moisture contents (16 and 18%) were used in this study. Exceptionally high drying temperatures would likely have detrimental effects on seed quality with higher moisture seed.

In modern soybean seed production, seeds are often left in the field to undergo maturation drying. Seed corn producers harvest seed much earlier (PM) in order to avoid the reduction in seed quality associated with field weathering. Thus, it is understandable that
research focus has placed on drying maize seeds rather than soybean seeds. Drying high moisture corn seed at high temperatures will impair cellular membranes, (Herter and Burris, 1989) and likely reduce seed quality. Partially drying maize seed at a low temperature (preconditioning) for a period of time before successive high temperature drying was found to reduce the negative effects of drying high moisture maize seed. It was also shown that seeds acquired a higher level of desiccation tolerance in a shorter amount of time when exposed to preconditioning (Herter and Burris, 1989). Perdomo and Burris (1998) studied changes in maize seed embryo during artificial drying at four preconditioning temperature and humidity levels. Respiration rates were lowest when seeds were preconditioned at 20°C at either 35 or 90% RH. The highest maize seed quality was obtained at moderate temperature (35°C) and low RH (25%) (Perdomo and Burris, 1998). The importance of slow embryo drying (preconditioning) on seed viability and vigor has also been shown by (Cordova-Tellez and Burris, 2002b). A transmission electron microscope study on lipid body alignment during acquisition of desiccation tolerance in maize seed showed that rapid drying may prevent lipid body alignment along the plasma membrane. The disorganization of lipid bodies is believed to be associated with low germination and vigor (Cordova-Tellez and Burris, 2002a).

**Harvesting and Drying Seeds within Pods**

To study the characteristics of soybean maturation and its processes, Burris (1973), Adams and Rinne (1981), and Adams et al. (1983) dried soybean seeds within intact pods. Samarah (2005) studied the effect of drying seeds within pods on the germination of common vetch (*Vicia sativa* L.), which is an important forage and feed crop grown in the Mediterranean region. Common vetch pods were harvested at five pod developmental stages: beginning seed fill (BS), full size
seed (FS), greenish-yellow pod (GY), yellow pod (Y), and brown pod (B). Each was subjected to three drying treatments that included drying seeds with pods removed, drying seeds within pods, and drying seeds within pods still attached to the whole plant (Samarah, 2006). It was found that seeds dried within pods showed higher standard germination (Samarah, 2005; 2006) and vigor (Samarah, 2006) than seeds dried without pods at early stages of development (BS and FS). Samarah et al. (2009) produced a soybean study that used ambient (25°C) and heated (29°C) air to dry seeds and pods. Seed quality was measured by standard germination and accelerated aging tests. It was found that drying seeds within intact pods preserved germination at FS and GY stages and vigor at FS, GY, and Y stages in comparison with depodded seeds. The drying temperature and treatment had no effect on seed quality at later maturity stages (Y and B) due to the fact that these seeds had likely acquired desiccation tolerance. Drying temperature did not affect accelerated aging germination in podded seeds at all maturities except FS (Samarah et al., 2009). These results may be useful as a decision-making tool in soybean production regions where weathering may affect soybean seed quality after PM is reached (Samarah et al., 2009).

**Soybean Seed Quality Testing**

The term “seed quality” can be quite broad and encompass multiple characteristics. Characteristics may include viability, germination, vigor, physical or genetic purity, and physical quality. Many times, researchers focus on one or two aspects of seed quality. For example, a published paper may study effects of specified influences on seed quality; however, seed quality is determined through standard germination only. In this example, results will only be inferable under ideal growing conditions because of the nature of standard germination testing. Due to this limitation, it can be ascertained that testing for multiple seed quality aspects allows
researchers a wider inference when making conclusions. The terms viability and germination, in relation to seed quality, are often defined with differing characteristics, i.e., radicle protrusion versus normal seedling, respectively. Many times they are considered synonymous. It is important to note the distinction, if possible, in research articles pertaining to seed quality.

*Standard Germination Test*

The standard germination test gives an accurate measurement of field emergence under favorable conditions. Soybeans are germinated in rolled brown paper towels or crepe cellulose paper at 25°C for seven days. Seedlings are evaluated as either normal, abnormal, or dead according to Association of Official Seed Analysts (AOSA, 2003). There are inherent problems solely relying on this test to determine seed quality. Delouche and Baskin (1973) realized two factors relate to the inadequacy of the standard germination test: the philosophy of germination testing and the nature of seed deterioration. In standard germination testing of soybeans, interpretation of seedlings is grouped into three categories: normal, abnormal, and dead. Evaluation provides no distinguishable difference between weak, semi-weak, and strong seedlings (Delouche and Baskin, 1973). However, results from Egli and TeKrony (1995) suggest that planting soybean seed with a standard germination ≥95% will result in adequate plant performance. The inadequacies in standard germination testing paved the way for novel methods to differentiate seed vigor of various seed lots. Two common methods to test for seed vigor are the accelerated aging test and the electrical conductivity test.
Seed vigor

Seed vigor testing and standardization have improved greatly in the past 40 years. Early concepts of seed vigor were developed to describe characteristics not recognized by the standard germination test (Delouche and Caldwell, 1960). Delouche and Caldwell (1960) described the variability associated with testing seed vigor and noted the inconsistencies within and between testing laboratories. From this early research, great improvements have been made to standardize vigor testing protocols. The Association of Seed Analysts (AOSA, Ithaca, NY) and International Seed Testing Association (ISTA, Basserdorf, Switzerland) both publish handbooks which describe these vigor tests in detail. Two tests commonly used to test vigor are the accelerated aging and electrical conductivity tests.

Seed Vigor – Accelerated Aging

The accelerated aging (AA) test was first described by Delouche and Baskin (1973) as a way to predict storability of seed lots; however, it is now a common way to measure seed vigor in a wide variety of crops. The accelerated aging test integrates many of the important characteristics desired in a vigor test. Vigor tests should be objective, rapid, uncomplicated, and inexpensive (AOSA, 2002). It was assumed that “the processes of deterioration under accelerated aging conditions are similar to those under ‘normal’ conditions – only the rate of deterioration is enormously increased” (Delouche and Baskin, 1973). In order to achieve this rapid deterioration, the accelerated aging test exposes small samples of seeds to adverse conditions for a prescribed amount of time (Delouche and Baskin, 1973). The accelerated aging test exposes seeds to two environmental conditions that hasten seed deterioration: high temperature and high humidity. The principle is that high vigor seeds will endure the stress
conditions and deteriorate at a slower rate than low vigor seeds (The Ohio State University, 2003). To assess the effects of aging temperature and humidity on the results; many other factors must be controlled. These guidelines are presented in vigor testing handbooks by AOSA (2002). Slight alterations in temperature control or sample size can cause variation in final seed moisture content or germination (Tomes et al., 1988). Results from the AA test are recorded as percent normal seedlings, similar to evaluation of normal seedlings in a standard germination test (AOSA, 2002). AA test results are often compared to standard germination results. AA-germination results similar to standard germination are considered high vigor; AA-germination results lower than standard germination are classified as medium to low vigor seed (AOSA, 2002). High, medium, and low vigor soybean seed lots have been classified based on ≥80%, 60 to 80%, or <60% AA-germination, respectfully, when related to field emergence under a wide range of conditions (Egli and TeKrony, 1995).

Direct relationships between soybean seed vigor and field emergence have been difficult to establish (Egli and TeKrony, 1995). Research conducted by Kulik and Yaklich (1982) evaluated the relationships of many vigor tests to field emergence. The authors found that the percent difference in the linear regression coefficient was 7% for the accelerated aging test, which should give consistent estimates of potential field emergence between years. However, it was noted that estimating potential field emergence and predicting field emergence were not synonymous, and that none of the included vigor tests should be used to predict field emergence (Kulik and Yaklich, 1982). Johnson and Wax (1978) tested multiple vigor tests to determine a relationship with field performance and found that only the cold test showed a consistently high correlation with field performance. However, seeds allocated to AA testing were incubated at high temperature and RH for only 32 h, less than half the time suggested by AOSA (2002).
Same seed lots planted at different dates and locations varied considerably in field performance, depending on seed bed conditions during germination and emergence (Johnson and Wax, 1978). More recently, studies have shown that the accelerated aging test shows great potential as a vigor test for prediction of field emergence in soybean seeds (Egli and TeKrony, 1995; Vieira et al., 2009b). Egli and TeKrony (1995) used field emergence index (FEI=mean field emergence / mean standard germination \times 100) to adjust for differences among seed quality tests. Field prediction accuracy for AA-germination levels of 80 or 90% remained near 100% until FEI approached 80. The authors concluded that no test accurately predicted field emergence with FEI levels below 80%. It was suggested that planting soybean seed with an AA of \geq 80% will ensure acceptable performance in many environments (Egli and TeKrony, 1995).

Seed vigor – Electrical Conductivity

The electrical conductivity (EC) test is an inexpensive, simple method for evaluation of seed vigor. Seeds are typically placed in deionized water for a prescribed amount of time (24 h) before a reading is taken using a solution analyzer. Initial seed moisture may influence EC readings, thus it may be necessary to adjust seed moisture content between 10 and 14% prior to testing (Loeffler et al., 1988; AOSA, 2002). However, Hampton et al. (1992) found that little variation in conductivity occurred at soybean seed moisture contents between 10 and 22%. Seed moisture contents below 10% significantly increased conductivity because of imbibitional damage (Hampton et al, 1992). Seed size may also influence results, which is why EC is typically expressed as $\mu$S cm$^{-1}$ g$^{-1}$ (AOSA, 2002). The EC test is an indicator of mechanical damage as mechanical injury often leads to loss of integrity of seed coats, especially in large-seeded legumes (AOSA, 2002). Often times, mechanical damage is difficult to detect by visual
examination. Loeffler et al. (1988) found that EC tests have the ability to detect mechanically injured seeds that may elude visual detection. Although the EC test may be a useful indicator of soybean seed quality, it will not represent damage that may be caused by pathogenic fungi. Seeds infected with high amounts of \textit{Phomopsis} sp. or \textit{Cercospora kikuchii} did not exhibit increased conductivity of respective seed soak solutions (Loeffler et al., 1988).

Electrical conductivity is the ability of material to transmit an electrical current. In seed vigor testing, the EC test can detect poor membrane structure of low vigor seeds. The soybean EC test is based on cellular membrane integrity and measures the amount of electrolyte leakage, which includes amino and organic acids. The higher the amount of electrolyte leaked into the deionized water, the lower the vigor of the seed. The amount of ions released can be considered a measure of the physiological potential of seed (Colete et al., 2004). Disorganized membranes cannot become a selective membrane and cannot guard against solute leakage (AOSA, 2002). During early seed imbibition, the ability of cellular membranes to reorganize and repair damage that occurred during seed development, harvest, and post-harvest will directly affect seed vigor (AOSA, 2002). High vigor seeds will repair damaged membranes more quickly than low vigor seed, thus electrolyte leakage is greater in low vigor seed than in medium to high vigor seed. The cation with the greatest concentration in seed soak water has been potassium (AOSA, 2002). Other constituents have been related to seed soak conductivity, such as various cations (calcium, magnesium, sodium), amino acids, proteins, enzymes, and organic acids (Powell, 1986; Panobianco et al., 2007). The EC test is both a physical and biochemical test. The success of the EC test follows a physical principle in that the seed soak solution is directly quantified, yet, it is considered a biochemical test because the discharge of electrolytes is a result of changes in cellular membranes. The intensity of the change in cellular membrane is proportional to seed
deterioration rate (AOSA, 2002). Vieira (1994) considered EC of high vigor seed to be within 60 to 70 µS cm\(^{-1}\) g\(^{-1}\) and EC of medium vigor seed to be within 70 to 80 µS cm\(^{-1}\) g\(^{-1}\). Seed lots with EC up to 110 µS cm\(^{-1}\) g\(^{-1}\) were found to have acceptable field performance under optimum field and environmental conditions (Vieira et al., 1999a; 1999b; 2004).

Much like the accelerated aging test, studies have attempted to link EC values with soybean seedling emergence. Vieira et al. (1999b) found that significant correlations existed between EC and field emergence; however, it is recognized that the degree of association can change due to the environmental conditions between years (Vieira et al., 1999a; 1999b; Colete et al., 2004). The EC test can be a useful tool in seed vigor determination and has been found to be negatively correlated with the standard germination, accelerated aging, and field emergence tests (Vieira et al., 1999b).
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CHAPTER 2. EARLIER HARVEST AND DRYING OF SOYBEAN SEED WITHIN INTACT PODS MAINTAINS SEED QUALITY

A paper to be submitted to *Crop Science*

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Abstract

Soybean [*Glycine max* (L.) Merr.] seed quality (viability and vigor) is critical to seed producers, emphasizing the need to maximize the quality of the harvested seeds. Currently, soybean seeds are harvested at a moisture content of \( \leq 160 \text{ g kg}^{-1} \), similar to the moisture content of harvested soybean grain. However, soybean seed quality peaks at physiological maturity (PM). Allowing soybean seeds to desiccate in the field increases vulnerability to seed deterioration, disease, and harvest losses. Early harvest of soybean seeds and drying within intact pods might maintain seed quality. Our research examined the effect of maturity stage (green-, yellow-, or brown-pod), drying temperature (27°C ± 2, 31°C ± 2, or 41°C ± 2), and pod integrity (pod intact or removed) on soybean seed quality. Seeds were harvested in 2009 and 2010 and dried within stacked tray driers. Drying podded, yellow-pod maturity seeds at ambient temperature (27°C ± 2) protected seeds from rapid desiccation and seeds exhibited similar seed quality characteristics as those harvested at brown-pod maturity stage. A drying temperature of 41°C ± 2 greatly reduced seed quality at both levels of pod integrity for immature harvested seeds (green-pod). Harvesting soybeans at the yellow-pod stage has the greatest potential for
early harvest while maintaining seed quality. Pod integrity did not affect seed quality of brown-pod harvested seeds at any of the drying temperatures.

**Introduction**

The importance of soybean [*Glycine max* (L.) Merr.] seed quality (viability and vigor) has increased in breeding programs due to the emphasis on early planting and rapid, uniform emergence in high-yielding, grain production environments. In the last decade, prices of transgenic soybean seed have increased more than 220% (USDA-NASS, 2010). The higher price of soybean seed has caused seed producers to seek new ways of maximizing seed quality. Seed development, maturity, and harvest management are critical considerations for soybean seed producers to maintain high seed quality, while minimizing field losses.

Harvesting soybean seeds after harvest maturity may result in lower seed quality due to a wide range of environmental factors (TeKrony et al., 1980). Soybean seeds exposure to alternate wetting and drying in a production environment may result in embryo deterioration and lower seed quality (Moore, 1971). Krul (1978) showed that soybean pods contained unknown substances that blocked imbibition of water by seeds; pods that were rehydrated before harvest showed increases of these diffusible substances. Soybeans harvested at less than 130 g kg\(^{-1}\) moisture content exhibited greater susceptibility to imbibitional damage (Hobbs and Obendorf, 1972), as well as greater field losses due to shattering. Vertucci and Leopold (1984) and LeVan et al. (2008) concluded that imbibitional damage became severe when seed moisture content was < 80 g kg\(^{-1}\). Drying high-moisture soybean seeds within their pods may provide protection against rapid desiccation at ambient or heated temperatures (Samarah et al., 2009). One way to
reduce decreased seed quality due to weathering is to harvest soybeans before harvest maturity is reached.

Soybean seeds undergo many physiological and biochemical changes during development and maturation, and these changes are essential for seed germination (Miles et al., 1988). Physiological maturity occurs when a seed has accumulated its maximum dry weight (Shaw and Loomis, 1950; Harrington, 1972). Miles et al. (1988) described PM as maximum accumulation of seed dry weight and complete transition from green to yellow color, whereas Crookston and Hill (1978) concluded that seed shrinkage can be a reliable indicator of PM. It has been reported that seed quality is greatest when PM is reached naturally (Harrington, 1972; Wahab and Burris, 1971; Miles et al., 1988). However, Adams and Rinne (1981) proposed that soybean seed maturation is independent of the parent plant and can be imposed during many stages of development. By allowing freshly harvested, immature seeds to air-dry within intact pods, the authors concluded that maturation can be artificially imposed and still yield viable seeds. Air-drying seeds within intact pods terminated seed expansion, maintained enzyme activity, and modified soluble proteins, which initiated the maturation process of immature seeds (Adams and Rinne, 1981).

Soybean seeds harvested at PM have high seed moisture content and need to be dried before storage. Seed moisture content at PM is variable, ranging from 500 to 620 g kg\(^{-1}\) (Howell et al., 1959; Crookston and Hill, 1978; Tekrony et al., 1979; Samarah et al., 2009). The seed quality of high moisture soybeans can be maintained by slowly drying seeds. One potential method to slow the rate of seed dehydration is to harvest and dry soybean seeds within intact pods (Burris, 1973; Adams and Rinne, 1981). Previous studies have shown that seed germination and vigor of common vetch was preserved when seeds were dried inside intact pods.
Samarah et al. (2009) found that drying soybean seeds within intact pods using heated (29°C) or ambient (25°C) air improved germination and vigor of seeds harvested at earlier developmental stages (green- and yellow-pod stages). However, the role of pod integrity in maintaining soybean seed quality under different harvest and drying regimes is not fully understood. Similarly, the maximum drying temperature at which intact pods no longer preserves good seed quality has not yet been determined.

The purpose of our study was to determine the effects of drying temperature and pod integrity on soybean seed quality for seeds harvested at three maturity stages (green-, yellow-, and brown-pod color). We dried seeds within intact pods and with pods removed to determine the influence of pods and the effectiveness of slow desiccation on soybean seed quality. Standard germination, accelerated aging (AA), and electrical conductivity (EC) tests were used as indicators of seed quality.

**Materials and Methods**

Seeds from five soybean cultivars [*Glycine max* (L.) Merr.] were grown and harvested in Boone County, IA, in 2009 and 2010. Cultivars were selected for their similar maturation rates to aid in timing of harvest. The experimental design was arranged as a triple-split arrangement in a randomized complete block design with three replications. The whole-plot was variety, the split factor was pod maturity stage, the split-split factor was drying temperature, and the split-split-split factor was drying treatment. The cultivars Norfolk-741RR and Austin-643RR were used in 2009, and the cultivars Jackson-934RR2Y, Stine-2862-4/SHIMK 936, and Cherokee-1024 RR2Y/BIN 21 were used in 2010. Pods were hand harvested at three maturity stages based
on the criteria outlined by Samarah et al. (2009): full-size green pods, yellow pods, and brown pods. Pods were harvested at full-size green, yellow, and brown stages on 20 Sept., 29 Sept., and 7 Oct. in 2009 and 5 Sept., 17 Sept., and 28 Sept. in 2010, respectively. Seeds were removed from pods by hand and exposed to the drying treatments within 6 h of the harvesting time. Podded and depodded seeds were dried using forced air in stacked tray driers (Navratil and Burris, 1982) at ambient temperature ($27^\circ C \pm 2$) or two heated air temperatures ($31^\circ C \pm 2$ or $41^\circ C \pm 2$).

Drying temperature was monitored using thermocouples (OMEGA Engineering, Inc., Stamford, CT) placed near the bottom of the stacked tray driers. Temperatures were recorded every 300 s by an OMB-DAQ-55 Data Acquisition Module (OMEGA Engineering, Inc., Stamford, CT). Relative humidity was monitored at 300 s intervals using a CS500 Temperature and Relative Humidity Probe (Campbell Scientific, Inc., Logan, UT).

Initial seed moisture content was determined by oven drying seeds at $105^\circ C$ for 72 hours. Three samples of 20 seeds from each variety and replicate were used to determine the average seed moisture content. Seed moisture content was expressed as the loss in weight divided by the initial weight of the seed (on a wet-weight basis). Seed dry weight (mg seed$^{-1}$) was recorded to determine PM. Seeds were dried to moisture contents between 90 and 130 g kg$^{-1}$, and were stored in sealed, plastic containers. Seeds were stored in a controlled environment of $10^\circ C$ and $50\% \pm 5$ relative humidity until seed quality testing could commence ($< 5$ months for both years).
Standard Germination

The standard germination test was conducted for the harvested seeds from different varieties, maturity stages, and treatments according to the Association of Official Seed Analysts (AOSA) rules (AOSA, 2003); however, 50 seeds were used per replicate. Seeds were firmly placed on moistened crepe cellulose paper and were held under germination conditions in a temperature controlled chamber at 25°C for seven days with four hour alternating light periods. Germination was defined as the percentage of normal seedlings based on AOSA (2003) rules. Abnormal seedlings were those that could not be classified as normal seedlings, and dead seeds were those softened or decayed at the time of evaluation. Hard seeds were those that did not imbibe water during the test and were not considered normal seedlings.

Accelerated Aging

Soybean seed vigor was measured using the accelerated aging test conducted in accordance with AOSA rules (AOSA, 2002), with exception to seed number per replicate. Fifty-five seeds from each treatment were individually placed on a wire-mesh tray suspended above 40 ml of distilled water, which was placed inside a clear plastic container measuring 11 × 11 × 3.5 cm. Containers were covered and incubated at 41°C for 72 h according to the Seed Vigor Testing Handbook (AOSA, 2002). After incubation, 50 seeds from each treatment were planted on moistened sheets of crepe cellulose paper and covered with a 2-cm layer of moistened sand (800 ml of distilled water per 45 kg of sand). Seeds were then allowed to germinate in a temperature controlled chamber at 25°C for seven days with 4 h light intervals. Evaluations of normal and abnormal seedlings were performed in accordance with AOSA rules (2003).
Electrical Conductivity

Fifty seeds of each treatment were weighed to the nearest 0.01 g and soaked in 75 mL of deionized water within 0.47 L plastic cups. Cups were covered with aluminum foil and seeds were allowed to hydrate at 25°C for 24 hours. Electrical conductivity was measured immediately (within 15 minutes) after the 24 hour hydration period with a Solution Analyzer Model 4603 (Amber Science, Inc., Eugene OR). The analyzer was recalibrated every 24 readings using 718 Micro-Mho ± 1 @ 25 Degree C 0.005N KCl solution (Amber Science, Inc., Eugene OR). Results were expressed as μS cm⁻¹ g⁻¹.

Data Analysis

Seed quality data were analyzed using a generalized linear models (GLM) procedure (SAS Institute Inc., 2009). Years were analyzed separately. To expand inference, varieties were considered random and pooled into proper error terms. Seed quality data, seed moisture content, and seed dry weight means were separated using Student’s t-test at \( P \leq 0.05 \) via LSMEANS statement (SAS Institute Inc., 2009).

Results

Seed Moisture Content and Dry Weight at Harvest

Average initial seed moisture content at green and yellow maturity stages were similar in 2009 and 2010; however, seed moisture content at brown pod stage was greater in 2009 than in 2010 (Table 1). Seed moisture content decreased by 200 g kg⁻¹ from 2009 to 2010 in brown-pod harvested seed. In both years, seed moisture content decreased steadily as the seeds matured.
The seed moisture content at PM averaged 520 g kg\(^{-1}\). The maximum seed dry weight (171.1 and 124.6 mg seed\(^{-1}\)) was attained at yellow-pod maturity in 2009 and 2010, respectively. Varietal differences of seed moisture content within harvest stage did not occur with the exception of brown-pod maturity stage in 2009 (data not shown).

**Standard Germination**

The analysis of variance indicated main effects and interaction effects of maturity stage, drying temperature, and drying treatment on the percentage of normal seedlings in 2009 and 2010 (Table 2). Physiologically immature soybeans harvested at the green-pod stage exhibited low germination (< 79%) in 2009 and 2010 (Tables 3 and 4). Pod-dried soybean seeds had a higher germination percentage than depodded seeds when pods were harvested at green- and yellow-pod maturity stages. Podded seeds harvested at green-pod maturity and dried at 27°C ± 2 or 31°C ± 2 germinated 50 to 70 percentage points greater than germination percentages for depodded seeds (Tables 3 and 4). The low germination of the depodded dried seeds was mainly due to the high percentage of dead seeds at evaluation time (data not shown). The highest drying temperature (41°C ± 2) proved detrimental to seed viability (< 10% germination) regardless of whether seeds were podded or depodded when harvested at green-pod maturity. Seeds harvested at yellow-pod stage and dried within intact pods (podded) showed a 14 to 25% increase in germination across all drying temperatures compared to depodded seeds; however, germination percentage did not change between drying temperatures of both drying treatments (Tables 3 and 4). Yellow-pod maturity seeds dried within pods (podded) showed no difference in germination compared to brown-pod seeds at the two lowest drying temperatures in 2009 (Table 3) and across all temperatures in 2010 (Table 4). Seeds dried without pods (depodded) showed an
increase in germination as soybean pods matured from green to brown-pod stage in 2009 and 2010. Soybean seeds harvested at brown-pod stage showed no difference across drying treatments in both years.

**Accelerated Aging**

Analysis of variance for AA tests showed differences among main effects in 2009 and 2010. A three-way interaction among maturity stage, drying temperature, and drying treatment was not significant in 2009 and 2010 (Table 2).

Seeds harvested at the yellow- and brown-pod maturity stages had the highest AA-germination; however, overall germination after AA test was lower in 2010 than in 2009 (Tables 3 and 4). Immature soybeans harvested at the green-pod stage showed low overall AA-germination in both years (Tables 3 and 4). In 2009, however, there was an increase in AA-germination for seeds dried in intact pods at the 27°C ± 2 drying temperature compared with depodded seeds at similar maturity (Table 3).

In 2009, drying the seeds within intact pods increased the AA-germination compared with the depodded seeds when seeds were harvested at yellow-pod maturity and dried at the 27°C ± 2 and 31°C ± 2 drying temperatures (Table 3). This increase in AA-germination was not observed in 2010 (Table 4). Accelerated aging germination was not affected by the drying temperatures or drying treatments (podded or depodded) at yellow-pod maturity stage (Tables 3 and 4). Drying soybean seeds within intact pods did not increase AA-germination at the brown-pod maturity stage in 2009 and 2010. In 2010, depodded seeds harvested at the brown-pod stage and dried at 31°C ± 2 had a higher AA-germination than seeds dried within intact pods (Table 4). This observation was not seen in other maturity stages or drying treatments.
Electrical Conductivity

The EC test measures the amount of electrolyte leakage from seeds soaked in deionized water for a prescribed amount of time (24 h). The results from this test are inversely related to seed quality; the higher the amount of electrolyte leakage, the lower the seed vigor. Drying podded, green-pod maturity seed at 41°C ± 2 increased EC by 390% in 2009 (Table 3) and 480% in 2010 (Table 4), compared with drying podded, green-pod maturity seed at 27°C ± 2.

Depodded, green-pod maturity seed had very high EC values (>270 µS cm⁻¹ g⁻¹) across all drying temperatures. Low amounts of seed electrolyte leakage (<60 µS cm⁻¹ g⁻¹) occurred in podded, green-pod maturity seed dried at 27°C ± 2 in both years (Tables 3 and 4).

The EC of depodded, yellow-pod maturity seed did not change with various drying temperatures in 2009 and 2010. Drying podded seeds with high temperature (41°C ± 2) at yellow-pod maturity did increase EC in both years; however, EC values did not change at drying temperatures of 27°C ± 2 and 31°C ± 2 (Tables 3 and 4). Podded, yellow-pod maturity seeds dried at 27°C ± 2 had low EC readings in 2009 (56.0 µS cm⁻¹ g⁻¹) and 2010 (57.8 µS cm⁻¹ g⁻¹).

The EC of brown-pod maturity seed ranged from 57.5 to 64.2 µS cm⁻¹ g⁻¹ in 2009 (Table 3) and from 53.5 to 58.4 µS cm⁻¹ g⁻¹ in 2010 (Table 4). In both years, no difference in seed EC occurred with different drying treatments (podded or depodded) and drying temperature (27°C ± 2, 31°C ± 2, or 41°C ± 2) at brown-pod maturity stage. Low EC values at the brown-pod stage were not significantly different from podded seeds dried with low temperature (27°C ± 2) at green- and yellow-pod maturity.
Discussion

Soybean seeds reached physiological maturity at the yellow-pod stage, results that are similar to previous studies performed by Samarah et al. (2009) and Miles et al. (1988). Immature seeds have the capacity for germination before maximum seed weight is reached (Obendorf et al., 1980), however, our results show that seed vigor may be unacceptable when harvesting immature seeds (green-pod stage) (Tables 3 and 4). Comparable to results by Adams et al. (1983), our results suggest that soybean seeds dried within pods showed slower rates of moisture loss than seeds with pods removed (data not shown). The slower rate of moisture loss helped improve seed viability in green- and yellow-pod maturity soybean seeds, which is similar to results from Adams et al. (1983) and Samarah et al. (2009). The increase of seed viability by drying immature soybean seeds within pods has also been reported by Adams and Rinne (1981), which supports their conclusion that drying soybean seeds within pods imposes the maturation process on immature seeds. Soybeans harvested before PM (green-pod stage) exhibited lower germination and vigor than those seeds harvested at the yellow-pod stage. Drying immature (green-pod stage) soybeans at high temperature decreased seed quality considerably, even when seeds were dried within pods. Harvest at the yellow-pod stage showed the greatest potential for early harvest of soybean seed while maintaining good seed quality characteristics.

Results from Samarah et al. (2009) showed an increase in AA-germination percentages in comparison with our results. In our study, AA-germination percentage decreased from 2009 to 2010. This decrease in AA-germination might be attributed to the decrease of seed size and seed weight in 2010 (Table 1). Seeds were placed in the aging boxes by count (55 seeds), not by weight, in order to ensure proper seed allocation for each test. This caused over-aging of the
2010 seeds (Table 4), which may be the cause of decreased AA-germination and low overall AA-germination (in both years) when compared with results from Samarah et al. (2009). Placing seeds within aging boxes by weight (42 g), rather than by number, would alleviate the issue of dissimilar aging between seeds of differing dry weights (Tomes et al., 1988).

The measure of EC from seed soak solution is an indicator of seed vigor. High EC readings are indicative of cellular membrane degradation and low seed vigor (AOSA, 2002). Vieira (1994) considered EC of high vigor seed to be within 60 to 70 µS cm\(^{-1}\) g\(^{-1}\) and EC of medium vigor seed to be within 70 to 80 µS cm\(^{-1}\) g\(^{-1}\). Seed lots with EC up to 110 µS cm\(^{-1}\) g\(^{-1}\) were found to have acceptable field performance under optimum field and environmental conditions (Vieira et al., 1999a; 1999b; 2004). Immature (green-pod) seeds dried without pods showed the highest EC values in 2009 and 2010. Lowest EC values (highest seed vigor) were measured in yellow-podded seeds dried at 27 and 31°C, and brown-podded seeds across all harvest treatments and temperatures (Tables 3 and 4). Our EC results confirmed results from the standard germination tests.

Evidence that the legume pod protects and maintains seed quality, as well as slows the rate of seed moisture loss during drying has been reported by Samarah (2005; 2006) and Samarah et al. (2009). However, these studies did not dry seeds with heated air beyond 29°C and did not use EC as a means to measure seed vigor. Our research provides seed quality data on seeds dried at two heated air temperatures (31°C ± 2, 41°C ± 2). Seed germination and vigor substantially decreased when immature soybeans (green-pod stage) were dried at 41°C ± 2 (Tables 3 and 4). Drying seeds within intact pods did not protect immature seeds against rapid desiccation at high temperature (41°C ± 2). The higher air temperature dried seeds too fast and
did not allow immature seeds to acquire desiccation tolerance, results that were consistent with those of Samarah et al. (2009).

Standard germination results suggest that seeds inside mature soybean pods (brown-pod stage) naturally acquired desiccation tolerance during seed maturation on the parent plants, which explained the lack of seed quality differences between drying treatments (pods intact and pods removed). Soybeans harvested at brown-pod stage and dried with pods removed exhibited similar seed quality characteristics as yellow-pod seeds dried within intact pods across all drying temperatures (Tables 3 and 4).

The results from this study suggest that the greatest potential for early soybean harvest is at the yellow-pod stage. Harvesting soybean seeds near physiological maturity requires drying the seeds to safe moisture contents for storage. Storing seeds at high moisture content will result in high respiration rates (Howell et al., 1959), which will decrease seed quality. These results highlighted the importance of drying temperature for maintaining seed quality while harvesting and drying seeds within pods. Our results also indicated that drying seeds at temperatures of 27°C ± 2 and 31°C ± 2 were best to maintain germination of podded dried soybeans harvested at the green-pod maturity stage. Seed quality can be maintained during drying if yellow- and green-podded seeds are dried within intact pods, which allows for slow desiccation. Harvesting and drying (at 27°C ± 2 and 31°C ± 2) seeds within intact pods has potential as a method that will permit seed producers protect their investment by removing seeds from fields before environmental factors decrease overall quality of the seed lot.

More research is needed to provide seed quality data on mechanically harvested soybean pods at multiple developmental stages. Equipment currently used to harvest fresh market vegetables (snap beans or peas) may provide a basis for developing and implementing protocols
in future large-scale field trials. Results from our standard germination and vigor tests (estimated by AA-germination and EC) indicated that drying seeds within intact pods maintained soybean seed quality when seeds were harvested at green- and yellow-pod maturity stages and subjected to drying temperatures of 27°C ± 2 or 31°C ± 2.

Acknowledgements

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References


Table 1. Average initial moisture content (wet-weight basis) and seed dry weight for all soybean varieties by pod maturity stage and year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Pod maturity stage</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moisture g kg⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Green 640 a†</td>
<td>527 b</td>
<td>395 c</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>638 a</td>
<td>510 b</td>
<td>191 c</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry weight mg seed⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>148.8 a</td>
<td>171.1 b</td>
<td>173.4 b</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>92.2 a</td>
<td>124.6 b</td>
<td>125.0 b</td>
<td></td>
</tr>
</tbody>
</table>

† Within rows, means followed by the same letter are not significantly different (P ≥ 0.05) according to Differences of Least Squares Means (Student’s t-test).
Table 2. Analysis of variance (ANOVA) of the standard germination test, accelerated aging test, and electrical conductivity of seed leachate for soybean seeds harvested at three pod maturity stages (full-size green, yellow, and brown) and exposed to two drying treatments (podded or depodded) at three temperatures (27°C ± 2, 31°C ± 2, or 41°C ± 2).

<table>
<thead>
<tr>
<th>Effect</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard germination</td>
<td>Accelerated aging</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pod maturity stage (MS)</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Drying temperature (DT)</td>
<td>***</td>
<td>*</td>
</tr>
<tr>
<td>MS x DT</td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td>Drying treatment (DTr)</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>MS x DTr</td>
<td>***</td>
<td>**</td>
</tr>
<tr>
<td>DT x DTr</td>
<td>***</td>
<td>ns</td>
</tr>
<tr>
<td>MS x DT x DTr</td>
<td>***</td>
<td>ns</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.
Table 3. Percentage of normal seedlings in standard germination and accelerated aging tests for soybean seeds harvested at three maturity stages and exposed to two drying treatments at three drying temperatures in 2009. Electrical conductivity (μS cm⁻¹ g⁻¹) of seed leachate also shown.

<table>
<thead>
<tr>
<th>Pod maturity stage†</th>
<th>Drying treatment‡</th>
<th>27 ± 2</th>
<th>31 ± 2</th>
<th>41 ± 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard germination</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Podded seeds</td>
<td>76.7 d$</td>
<td>78.3 cd</td>
<td>0.7 e</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>0.0 e</td>
<td>0.3 e</td>
<td>0.3 e</td>
</tr>
<tr>
<td>Yellow</td>
<td>Podded seeds</td>
<td>98.0 ab</td>
<td>96.3 ab</td>
<td>88.3 bc</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>78.0 cd</td>
<td>77.3 d</td>
<td>77.0 d</td>
</tr>
<tr>
<td>Brown</td>
<td>Podded seeds</td>
<td>99.7 a</td>
<td>99.7 a</td>
<td>99.7 a</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>98.7 ab</td>
<td>98.7 ab</td>
<td>98.3 ab</td>
</tr>
<tr>
<td>Accelerated aging</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Podded seeds</td>
<td>37.3 cd</td>
<td>17.7 def</td>
<td>0.7 ef</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>0.0 f</td>
<td>0.0 f</td>
<td>0.0 f</td>
</tr>
<tr>
<td>Yellow</td>
<td>Podded seeds</td>
<td>67.7 ab</td>
<td>65.0 ab</td>
<td>52.0 abc</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>26.3 cde</td>
<td>20.3 def</td>
<td>29.3 cd</td>
</tr>
<tr>
<td>Brown</td>
<td>Podded seeds</td>
<td>77.3 a</td>
<td>48.3 bc</td>
<td>48.7 bc</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>63.3 ab</td>
<td>70.3 ab</td>
<td>49.3 bc</td>
</tr>
</tbody>
</table>
Table 3. (continued)

<table>
<thead>
<tr>
<th>Electrical conductivity</th>
<th>μS cm⁻¹ g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Green</strong></td>
<td></td>
</tr>
<tr>
<td>Podded seeds</td>
<td>59.6 fg</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>299.8 a</td>
</tr>
<tr>
<td><strong>Yellow</strong></td>
<td></td>
</tr>
<tr>
<td>Podded seeds</td>
<td>56.0 g</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>113.2 c</td>
</tr>
<tr>
<td><strong>Brown</strong></td>
<td></td>
</tr>
<tr>
<td>Podded seeds</td>
<td>57.5 g</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>58.7 g</td>
</tr>
</tbody>
</table>

† Pod maturity stage based on soybean pod color as outlined in Samarah et al. (2009).
‡ Podded: seeds remained in pods during drying; Depodded: seeds removed from pods before drying.
§ Within seed quality test sections, means followed by the same letter are not significantly different (\( P \geq 0.05 \)) according to Differences of Least Squares Means (Student’s t-test). Data from each year and test were analyzed separately.
Table 4. Percentage of normal seedlings in standard germination and accelerated aging tests for soybean seeds harvested at three maturity stages and exposed to two drying treatments at three drying temperatures in 2010. Electrical conductivity (µS cm\(^{-1}\) g\(^{-1}\)) of seed leachate also shown.

<table>
<thead>
<tr>
<th>Pod maturity stage†</th>
<th>Drying treatment‡</th>
<th>Drying temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>27 ± 2</td>
</tr>
<tr>
<td>Standard germination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Podded seeds</td>
<td>73.8 f§</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>6.2 h</td>
</tr>
<tr>
<td>Yellow</td>
<td>Podded seeds</td>
<td>97.8 a</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>86.0 cde</td>
</tr>
<tr>
<td>Brown</td>
<td>Podded seeds</td>
<td>91.6 abc</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>91.1 abc</td>
</tr>
<tr>
<td>Accelerated aging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>Podded seeds</td>
<td>9.1 d</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>0.0 d</td>
</tr>
<tr>
<td>Yellow</td>
<td>Podded seeds</td>
<td>41.3 a</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>35.8 abc</td>
</tr>
<tr>
<td>Brown</td>
<td>Podded seeds</td>
<td>29.3 abc</td>
</tr>
<tr>
<td></td>
<td>Depodded seeds</td>
<td>39.8 abc</td>
</tr>
</tbody>
</table>
Table 4. (continued)

<table>
<thead>
<tr>
<th></th>
<th>Electrical conductivity</th>
<th>µS cm⁻¹ g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Podded seeds</td>
<td>52.5 g</td>
<td>106.9 d</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>307.5 b</td>
<td>273.3 c</td>
</tr>
<tr>
<td>Yellow Podded seeds</td>
<td>57.8 g</td>
<td>63.4 efg</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>82.6 def</td>
<td>83.4 de</td>
</tr>
<tr>
<td>Brown Podded seeds</td>
<td>55.4 g</td>
<td>55.4 g</td>
</tr>
<tr>
<td>Depodded seeds</td>
<td>53.5 g</td>
<td>55.6 g</td>
</tr>
</tbody>
</table>

† Pod maturity stage based on soybean pod color as outlined in Samarah et al. (2009).
‡ Podded: seeds remained in pods during drying; Depodded: seeds removed from pods before drying.
§ Within seed quality test sections, means followed by the same letter are not significantly different \((P \geq 0.05)\) according to Differences of Least Squares Means (Student’s t-test). Data from each year and test were analyzed separately.
CHAPTER 3. GENERAL CONCLUSIONS

General Discussion

Soybean seeds reached PM at yellow-pod stage, consistent with finding from Samarah et al. (2009) and Miles et al. (1988). We found that slow drying soybean seeds within pods maintained germination and vigor at green- and yellow-pod maturity stages. Most seeds harvested at green-pod maturity and dried (at all temperatures) without pods were dead. These seeds, harvested at 64% moisture, had not yet reached PM and did not acquire desiccation tolerance; however, green-podded seeds dried at low temperature exhibited significant increases in standard germination percentage and EC. The effect of drying temperature and treatment on seed quality of pods harvested at brown stage was non-existent. These seeds had acquired desiccation tolerance and were able to tolerate artificial drying, even in depodded seeds. EC results (high-, medium, and low-vigor seed) resembled results from standard germinations in 2009 and 2010. Overall AA-germination was low in both years because of possible over-aging of seeds due to applying AA conditions according to seed number instead of weight; however, EC data provided us with a solid understanding of vigor on tested seeds. Seeds harvested at yellow-pod maturity (~50%) were found to be best suited for podded drying at low (27°C) and medium (31°C) temperatures. It would be safe to assume that harvesting seeds between yellow- and brown-pod stages and drying within pods at low temperatures maintains seed quality.

Recommendations for Future Research

As I’ve learned throughout my post-graduate career, a good research project will lead to questions that have yet to be answered. Combining information from ours and past research
provides a foundation for many other projects dealing with early harvest and drying of soybeans within intact pods. There are smaller scope studies that may be accomplished with less investment; however, larger scale studies should also be considered in order to widen inference and scope of future results and conclusions. Cooperation with entities such as seed companies, seed dryer manufacturers, or the Iowa Soybean Association should be considered for these large-scale projects.

**Small-scale studies**

A long-term study should be considered with continued soybean pod harvesting and drying studies conducted across multiple years with similar soybean cultivars. These should be conducted to validate ours and past research and to gain further understanding of the relationship between pod maturity and seed quality characteristics.

We have found that harvesting soybean seeds and drying (low temperature) within pods maintains germination and vigor. It would be important to study the relationship between seed quality and yield produced from seeds harvested and dried within soybean pods, since this is an important characteristic for seed producers.

Corn seed can be preconditioned for a specified amount of time before be subjected to high heat. This allows for increased seed quality due to proper lipid body alignment within plasma membranes (Herter and Burris, 1989; Cordova-Tellez and Burris, 2002). A similar principle may also apply for soybeans harvested at high moisture contents. Preconditioning of high-moisture soybean seeds may allow for high temperature drying without the devastating effect on seed quality that our research showed.
Concerns regarding storage of soybeans pods should be considered for future research. Logistical constraints may not allow soybean seeds to be removed from pods succeeding the drying operation. These podded soybean seeds will need to be safely stored until subsequent conditioning can ensue. Storing large amounts of podded soybeans may present difficulties as far as the pod producing unwanted microclimates around seeds, which may increase seed deterioration.

TeKrony et al. (1984) found that delaying soybean harvest past harvest maturity increased *Phomopsis* sp. infection and decreased seed quality. Harvesting soybeans at green- or yellow pod stage may decrease the incidence of certain diseases. This could be accomplished by testing seeds via blotter tests in an experimental design similar to the one outlined in Chapter 2.

*Large-scale studies*

We have provided evidence that soybean seed quality can be maintained if seeds are dried within pods at high moisture contents; however, large-scale adoption of these techniques will require economic and logistical studies. Seed producers are not likely to adopt these harvest and drying techniques if it doesn’t make economic or logistical sense. A possible economic boon may be in the form of increased equipment use in joint corn/soybean production facilities. Operations in these plants only occur during peak periods during the harvest season. Using this equipment to dry and condition both corn and soybean seed will likely increase efficiency of production operations.

Large-scale high-moisture pod harvest occurs frequently in fresh vegetable production. It will be important to begin collaboration with pod harvest implement manufacturers, seed-drier
manufacturers and seed industry professionals to begin large-scale soybean pod harvest and drying studies.

Harvesting soybeans within pods may also decrease the amount of dirt or foreign material that adheres to seed. Many soybean seed production plants are beginning to employ color sorters to differentiate high and low quality seed. Seed coat color can be an important characteristic in the production of food-grade soybean seeds, i.e., tofu production. Keeping seeds clean may allow for a reduction in the amount of seed that is discarded from dirt or debris clinging to seeds.

References


**Fig. 1.** Drying time for soybean seeds harvested at three pod maturity stages, three drying temperatures and two drying treatments in 2010
Fig. 2. Drying time for soybean seeds harvested at three pod maturity stages, three drying temperatures and two drying treatments in 2010.
ACKNOWLEDGMENTS

My time as a graduate student at Iowa State University has been invaluable to say the least. I would like to take the time to thank family, friends, and colleagues that have made my time at this institution truly memorable.

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I would like to thank Dr. Ken Moore for his patience and assistance with statistical analysis. Tremendous gratitude goes out to Dr. Nezar Samarah for his advice and help with our manuscript. I would also like to thank Alan Gaul. Much of my work with seed drying was facilitated by his expertise.

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