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STRATEGIES *For Improving*
Physiological Seed Quality

A Conceptual Framework for Seed Quality Related Research and Development

MAFES
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Strategies for Improving Physiological Seed Quality

A Conceptual Framework for Seed Quality Related R & D

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Preface

In 1985, James C. Delouche, the senior author, was invited to present the keynote paper in a conference at the Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, on Research and Training in Seed Production and Technology (*Investigacion y Capacitacion en Produccion y Tecnologia de Semillas*). The recommended topic was New Directions in Seed Research (*Nuevos Caminos en la Investigacion sobre Tecnologia de Semillas).* As part of the preparation for the address, seed research — past, present, and future — was reviewed and contemplated, with emphasis on the many works by staff and graduate students in Agronomy-Seed Technology. As the process evolved, it became quite clear that research had been, and would likely continue to be, sharply focused on maintenance and improvement of the physiological quality and performance potential of seeds. Seemingly, without conscious design, a multi-direction research and development (R & D) strategy had emerged. It was apparent that MSU's seed technology group had been at the forefront of developments since the late 1950's. The CIAT address, which introduced the idea of a multiple strategy approach to achievement of the main goals of seed research and identifying them as **maintenance, upgrading, genetic**, and **enhancement**, was very well received. A small paper of record based on the address was prepared for the Memorias (Delouche, 1985).

In 1992, Delouche was invited to present the keynote paper in the 4th Australian Seed Research Conference on the general topic of "Seed Quality Improvement Strategies." A rather long review-type paper was prepared, delivered, and published in the conference proceedings for limited circulation. Again, the multiple strategy conceptual framework for seed quality R & D explained and promoted at the conference aroused considerable interest and much followup discussion.

Later in 1992, E. R. Cabrera, another of the authors of this bulletin, presented a substantially modified version of the topic in Spanish in the triennial Pan American Seed Seminar, Santa Cruz, Bolivia. This, too, aroused much interest and led to significant followup discussion. In 1993, still another version of the "strategies" conceptual framework was presented in Spanish by Cabrera on invitation from La Universidad Autonoma Agraria Antonio Narro, Saltillo, Coahuila, Mexico.

Although there has been much interest in and discussion of the "strategies" concept, it has been mostly verbal. The small papers in the CIAT Memorias and in the Pan American Seed Seminar Proceedings are in Spanish and generally unavailable. The proceedings of the Australian Seed Research Conference, which contains the longer paper, had very restricted distribution. Since there is no permanent, accessible record of what seems to us to be a substantial contribution in seed science and technology, we decided to prepare a comprehensive publication to fully set forth the "strategies" conceptual framework and to showcase contributing research of our seed technology group, especially that of our graduate students.

Many persons contributed to the ideas and supporting data set forth in this bulletin and are cited in the customary manner. We must, however, specifically and gratefully acknowledge the contributions and support of our faculty colleagues: C. Hunter Andrews, Charles E. Vaughan, G. Burns Welch, Charles C. Baskin, and the late Howard C. Potts, all members of the team.

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Introduction

In the restricted but still rather broad area of physiological seed quality, major emphasis in research and development (R & D) during the past 100 years has been given to identifying the significant attributes of quality and establishing their relative importance; developing and improving quality evaluation methodologies; and devising production, harvesting, and conditioning systems and facilities for maintaining the quality of seeds from the time of maturation through the storage period and up to the next planting time. In other terms, a **quality maintenance strategy** has received major attention until fairly recently.The quality maintenance strategy was, and is, soundly based on a very substantial body of evidence and experience that most kinds of seeds in most production environments do attain a high level of quality at physiological maturity (Delouche, 1968, 1969B, 1973). Frequently, however, the physiological quality of seeds is rapidly and drastically eroded by unfavorable climatic conditions during the harvest and/or storage periods, and improper timing and incautious conduct of operations. Rather dramatic improvements in quality, therefore, can be achieved by adopting procedures and systems that reduce the rate of quality loss or deterioration, i.e., through implementation of the quality maintenance strategy.

Although the quality maintenance strategy is still valid and should continue as a major component of seed quality related R & D, it should not command near exclusive attention and should not claim most of the resources available, except, perhaps, in the less-developed countries where seed supply procedures and systems are still being sorted out. The changes underway in the technologies and economics of crop and plant production require much broader and more ambitious approaches based on multiple strategies (Delouche, 1983; Kent, 1984).

Crop producers must substantially reduce costs and minimize risks to maintain profitable operations. Since establishment of an optimum population of vigorous, uniform seedlings is the first and crucial step in economically successful crop production, producers would like to ensure that stand establishment is as fail-safe as feasible. Producers of "high-value" crops, such as vegetables and seedlings, are involved in intensely competitive and quality-conscious markets where the failure of seeds to germinate and emerge uniformly has severe consequences in terms of quality and acceptability of the product. In both producer groups, there is the strong feeling that the supplies of high quality and performance seeds are not adequate. If seed supplies issuing predominantly from the quality maintenance strategy are not adequately meeting the requirements of today, they will fall critically short of meeting future needs and expectations in a biotechnologically driven agriculture for a zero-defect seed delivery system. New approaches must be cultivated, and new strategies pursued. In this bulletin, a multiple-strategy approach for improving the physiological quality and performance of crop seeds is presented and rationalized as a conceptual framework for seed quality and related R & D. The examples and illustrations are largely from unpublished research from our group, the Mississippi State University Seed Technology Laboratory (STL), Department of Plant and Soil Sciences, and, especially from graduate students earning degrees in Agronomy-Seed Technology since 1960.

This publication is based on research done under projects MIS-6226, MIS-6227, MIS-6228, and previous State and Hatch projects in Agronomy-Seed Technology during the period 1960-1994. The specific sources of the data and information presented are indicated and fully cited in the References section.

Seed Quality Improvement Strategies

The many approaches to improvement of the physiological quality and performance of crop seeds can be roughly grouped into four strategies including the quality maintenance previously introduced. These are defined below in terms of objectives and illustrated in Figure 1.

- **Quality Maintenance.** The objective is to maintain the physiological quality of seeds for the desired period as near as economically feasible to the high level attained at physiological maturity through avoidance or minimization of factors and conditions that contribute to deterioration.
- **Quality Upgrading.** The objective is to improve or "upgrade" the quality of seed lots by removal of defective and low quality seeds to extent that is practical and economical; i.e., good quality seeds are concentrated in an "ac-

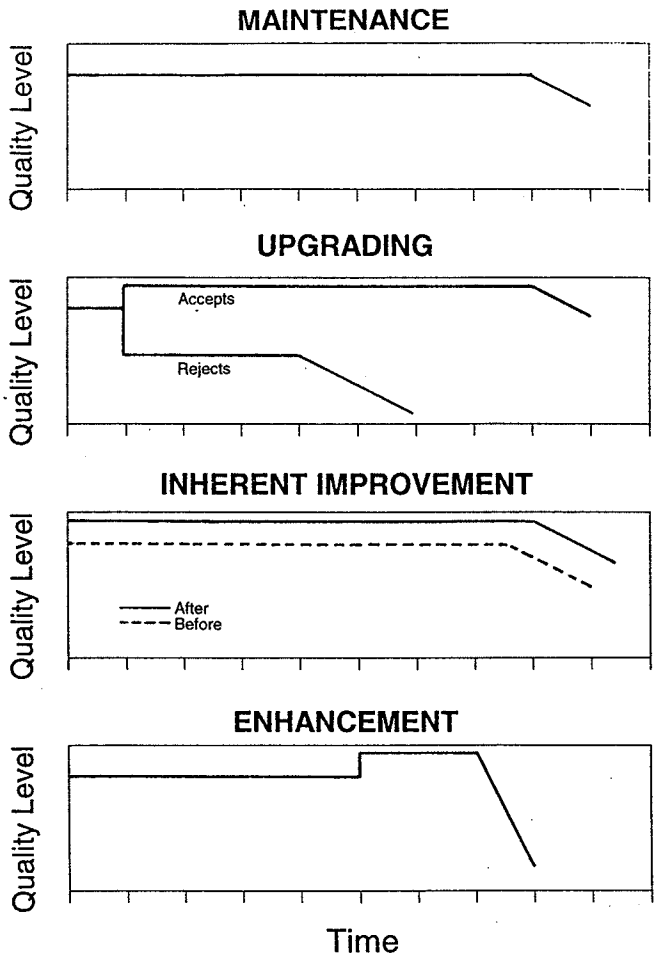

Figure 1. Graphical representation of four seed quality improvement strategies.

cept" fraction of the lot, while low quality, defective seeds are concentrated in a "reject" fraction.

- **Genetic Improvement.** The objectives are threefold: to facilitate maintenance of the physiological quality of seeds by increasing their inherent resistance (or tolerance) to factors and conditions that contribute to deterioration; to select for inherent physiological and/or physical properties that contribute directly to superior performance such as "seedling vigor and strength," or long mesocotyl; and to select for superior performance capabilities under conditions of temperature, moisture, biotic and mechanical impedance stresses in the seedbed.
- **Quality Enhancement.** The objective is to increase performance capabilities of seeds through special treatments above the level imposed by inheritance and achievable through normal conditioning and planting procedures; in a sense, to "supercharge" the seeds in terms of performance.

The strategies with the greatest potential for meeting the rising expectations of farmers and needs associated with the emerging role of seeds as the main delivery system for agrichemical and biotechnological "products" are genetic improvement and quality enhancement. These need to be complemented and supplemented by advances in quality upgrading procedures to compensate, as possible, for shortcomings in quality maintenance, and to concentrate the most suitable seeds for enhancement of their quality.

Quality Maintenance Strategy

Production and Preharvest Environment

Agriculture has been well served by the long-term implementation of the seed quality maintenance strategy. Successful systems have been developed for the production and supply of seeds for all kinds of crops ranging from peanuts to hybrid petunias. In many cases, these systems represent a sort of direct and wholesale application of the quality maintenance strategy.

Consider the locations of seed production in the United States and worldwide. Where possible, seed production for crops such as the forages, ornamentals, and vegetables is concentrated in arid, irrigated areas or in areas with a distinctive wet/dry season (Hawthorn and Pollard, 1954; Wheeler and Hill, 1957; Kernick, 1961; Austin, 1972; Delouche, 1980). The quantity of seeds produced is much greater under the full sunlight and scheduled water supply of the arid, irrigated areas; but that is not the main reason for the concentration of seed production in such areas. Seeds are produced in arid or wet/dry season areas because it is easier to **maintain** their quality. The **weathering** that is the scourge of seed production in areas well-watered by rain throughout the year is not a factor.

The relocation of a major portion of cotton seed production in the United States illustrates the importance of environment in production of high quality seeds (Delouche, 1986). When just about everything that could feasibly be done to maintain the quality of cotton seeds maturing under the frequently "rainy" and warm, humid conditions in the Midsouth and southeastern United States had been done, the results were still unsatisfactory. So, in the mid-1970's a major portion of cotton seed production was shifted to the arid west (Arizona), where seed quality can be better maintained and assured. Similarly, seed production for the cool season forage grasses and legumes was shifted after World War II from the eastern United States, where they are widely grown, to California and the Pacific Northwest, where environmental conditions for production of high yields of high quality seeds are nearly ideal (Wheeler and Hill, 1957).

The effects of the preharvest environment on maintenance of seed quality are evident in the summarized results from several seed maturation and field deterioration studies presented in Figure 2. The studies were all conducted at Mississippi State University in different years when "weathering" ranged from moderate to severe. The rates of field deterioration, i.e., loss of viability, were influenced by seed kind (in-

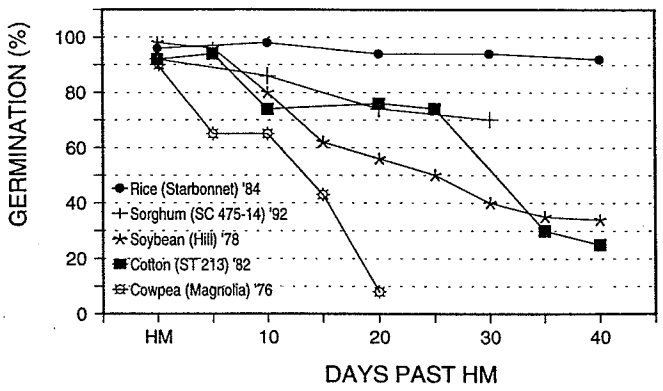

Figure 2. Reduction in germination of rice, sorghum, soybean, cotton, and cowpea seeds exposed to moderate to severe weathering conditions before harvest. HM = harvest maturity which was attained at the following seed moisture contents (approx.): rice, 22%; sorghum, 22%; cotton, 25%; soybean, 20%; cowpeas, 35% (Oropeza, 1976; Delouche, 1978; Bragantini, 1984; Pegase, 1993).

heritance) and the levels of environmental components of the weathering process. For example, rice seeds are inherently resistant to weathering and adverse storage conditions and maintained high germination through 40 days past the arbitrary field maturity stage. Cowpea seeds, on the other hand, are not very resistant to weathering and were exposed to the field environment during August when the daytime temperature exceeded 35 °C (95 °F).

In separate but related studies, Caldwell (1962) and Burdett (1977) demonstrated rather conclusively for cotton and soybeans, respectively, that the rate and extent of field deterioration of the seeds were highly correlated with the temperature during periods of rain, heavy dews, and high humidity: the warmer the temperature the greater the rate and extent of seed deterioration.

Harvest and Post-harvest Procedures

It has not, of course, been feasible or possible, even in the United States, to shift all seed production to the arid, irrigated areas to maintain quality through avoidance of weathering. Seeds of many major crops have to be produced in the areas of commercial production. Good quality soybean seeds, for example, can generally be produced throughout the areas of commercial production by close adherence to an array of tactics developed and deployed under the quality maintenance strategy. These include early and timely harvest to minimize field exposure, careful harvest to minimize mechanical damage, prompt drying as needed, adequate aeration, thorough conditioning (cleaning), and improved storage conditions to reduce deterioration (Delouche, 1969A, 1980).

Operational and quality assurance procedures that reduce mechanical damage and the interactive effects of mechanical damage and certain conditioning treatments have received special attention and contribute substantially to maintenance of seed quality in many important crops (Asgrow, 1949; Koehler, 1957; Delouche, 1969A, 1986; ARS, USDA, 1972). Some of the research results that attracted special attention to mechanical damage and treatment effects and interactions are presented in Table 1. Storability of cotton seeds was reduced by acid delinting, which mimics some sorts of mechanical abuse, mechanical damage, and the interaction of mechanical damage and treatment with systemic insecticides. It should be noted that the seeds were delinted by the wet or concentrated acid method, now obsolete, which exposed the embryonic tissue beneath cuts and punctures to concentrated sulfuric acid causing acid burns and enhanced phytotoxicity of the systemic insecticides.

Storage

Seeds have to be stored for periods ranging up to 8-9 months between harvest and planting of the next crop, and for even longer periods for the reserve or "security" seed stocks deemed essential, or at least highly desirable, by traditional farmers and many seed companies. Maintenance of the physiological quality of the seeds during the storage period has been a crucial task and problem since the beginnings of crop agriculture. Seeds in storage are consumed by insects, rodents, and other pests, and deteriorate rapidly under warm, humid conditions (Owen, 1956; Barton, 1961; Harrington, 1972; Delouche et al., 1973).

Two relatively recent major advances in seed storage were recognition of inherent differences in the longevity of crop seed kinds and varieties (Table 2, compare longevity of soybean and rice seeds), and recognition that maintenance of physiological quality and performance potential of seeds requires maintenance of vigor as well as viability (Delouche and Caldwell, 1960). These advances facilitated the development of economically efficient storage procedures and established the crucial criteria for evaluating both the storability

Table 1. Effects of mechanical damage, acid delinting, and seed treatment on the storability of cotton seeds under ambient conditions at Mississippi State, MS. (From Welch and Delouche, 1969.)

	Storage Period (mo.)						
Treatment[1]	0	6	12	18	24	30	36
	% Germination						
GR-8/MD	88ab	94a	92a	92a	90a	84b	72c
GR-32/MD	88ab	90a	90a	88ab	84b	74c	46d
AD-8/MD	96a	96a	92ab	88b	78c	66d	42e
AD-32/MD	94a	89a	89a	78b	66c	52d	6e
AD-8/MD-SI	90a	90a	86a	74b	60c	42d	12e
AD-32/MD-SI	88a	86a	74b	62c	38d	0e	—

[1]GR = gin run; AD = acid delinted; 8/MD = 8% mechanical damage; 32/MD = 32% mechanical damage; SI = systemic insecticide.
Means in rows not followed by the same letter differ significantly at the 0.05 level of probability according to Duncan's Multiple Range Test (DMRT).

Table 2. Germination percentages of high quality seed lots of 12 species during storage under ambient conditions at Mississippi State, MS. (From Delouche, 1973.)

Kind	Storage Period (mo.)					
	0	6	12	18	24	30
Bean, snap	98	96	96	90	92	90
Clover, red	94	94	88	73	60	58
Corn, field	98	98	96	96	90	85
Fescue, tall	95	90	85	78	37	12
Lettuce	96	90	82	68	21	2
Onion	96	90	42	6	0	0
Peanut, shelled*	96	93	60	5	0	0
Radish	98	98	98	92	95	92
Rice	94	92	94	92	90	90
Sorghum	96	96	93	86	82	78
Soybean	96	94	85	60	42	0
Timothy	96	96	86	76	37	0
Watermelon	98	98	96	95	90	88
Wheat	98	97	97	96	92	90

*Peanut seed hand-shelled.

of seed lots and the effectiveness of storage procedures and facilities (Delouche and Baskin, 1973).

Great strides in seed packaging and storage have been made under the quality maintenance strategy. The pioneering works of the Asgrow Seed Co. (1953) and Harrington (1963, 1972) opened the way for the adaptation of many types of moisture vapor-proof packaging materials for seeds, as they became available. This in turn made possible the global distribution of high-value vegetable and ornamental seeds. The factors affecting the storage life of seeds were identified and characterized and the general criteria for successful seed storage were established (Owen, 1956; Barton, 1961; Justice and Bass, 1978). The Seed Technology Laboratory group was especially active in assembling, adapting, and developing effective and efficient technologies for short-term storage of seeds in the humid temperate, subtropic, and tropic zones, and for longer-term storage in any environmental setting (Delouche et al., 1973; Welch and Delouche, 1973; see also Cromarty et al., 1982).

The effectiveness of moisture vapor-retardant packaging in maintaining seed quality during storage, along with some necessary precautions, and the important differences between maintenance of viability (germination) and maintenance of vigor, show up very well in some of the results from our seed storage studies presented in Tables 3 and 4. Soybean seeds packaged at 9.0% moisture in both polyethylene and multiwall paper bags maintained germination for 40 months under the excellent conditions at Mitchell Farms, Windfall, IN, but vigor significantly declined in 16 to 20 months more rapidly in the multiwall paper bags than in the polyethylene bags (Table 3). On the other hand, germination and vigor of seeds packaged at 11.6% moisture declined most rapidly in the polyethylene bags, which retarded drying. Under the very adverse storage conditions of 29 °C and 80% relative humidity, the protection provided by moisture vapor-retardant packages was especially dramatic (Table 4). Germination of corn seeds packaged in multiwall paper and cloth bags was negligible at 4 months, while those in polyethylene bags germinated above 80% even after 18 months.

Table 3. Germination, vigor, and moisture content of soybean seeds packaged at two initial seed moisture contents in polyethylene and multiwall paper bags during 40 months storage under ambient conditions at Windfall, IN. (From Delouche and Baskin, 1972.)

Bag Type[1]	Test[2] (%)	Storage Period (mo.)					
		0	8	16	24	32	40
		%					
		9.0% Moisture Content					
Polyethylene	SG	97a	96a	98a	97a	97a	96a
	AA	90a	89a	85a	77b	44c	9d
	MC	9.0	9.4	9.7	9.4	9.6	9.3
Multiwall	SG	97a	98a	96a	93a	98a	95a
	AA	90a	84a	72b	47c	19d	0e
	MC	9.0	10.4	10.0	10.2	10.5	10.8
		11.6% Moisture Content					
Polyethylene	SG	95a	96a	88a	49b	34cd	10d
	AA	88a	72b	49c	0d	—	—
	MC	11.6	11.6	11.8	11.8	11.8	12.0
Multiwall	SG	95a	95a	92a	92a	80b	63c
	AA	88a	80a	60c	60c	0a	—
	MC	11.6	10.4	10.1	10.1	10.4	10.4

[1] Polyethylene, 7-mil, maze seal; multiwall paper, 3-ply.
[2] SG = standard germination; AA = accelerated aging; MC = seed moisture content (w.b.)
Means in rows not followed by the same letter differ significantly at the 0.05 level of probability (DMRT).

Table 4. Germination and cold test response of corn seeds packaged in polyethylene and multiwall paper bags at 8.5% moisture content at intervals during storage at 29 °C and 80% relative humidity. (From Delouche and Baskin, 1972.)

Package Type[1]	Test	Storage Period (mo.)						
		0	2	4	8	12	16	18
		%						
Polyethylene	SG[2]	99	98	99	98	97	94	83
	CT	50	48	50	35	29	9	5
	MC	8.5	8.5	9.0	9.7	10.5	11.3	11.0
Multiwall	SG	99	30	1				
	CT	50	15	0				
	MC	8.5	16.7	15.5				
Cloth	SG	99	46	2				
	CT	50	10	0				
	MC	8.5	16.0	17.6				

[1]Polyethylene, 7-mil, maze seal; multiwall paper, 3-ply; cloth, cotton.
[2]SG = standard germination; CT = cold test; MC = seed moisture content (w.b.).

New Approaches

Several novel tactics for maintenance of seed quality have recently emerged and need to be pursued. West et al. (1985) and Henning (1990) extended the storage life of soybean seeds by coating them with various polyvinylidene chloride copolymer emulsions, a sort of individual seed packaging.

Impregnation or permeation of seeds with antioxidants, lipoxygenase inhibitors, and other viability "extenders" have produced interesting but mostly inconsistent results (Khan and Tao, 1973; Woodstock, et al., 1983; Rushing, 1988).

Cathodic treatments and treatments that permit operation of "internal" repair mechanisms appear to extend viability and even reverse "aging" under some conditions (Pammenter et al., 1974; Berjak and Villiers, 1972; Tilden and West, 1985).

Note must also be taken of the increasing recognition under the **genetic improvement strategy** of the role of the seed covering in maintenance of viability and vigor and seed performance, especially under marginal conditions (Potts, et al., 1978; Bragantini, 1984).

Unfinished Business

Substantial as they are, the achievements in terms of seed quality in both the arid irrigated areas and the areas of rainfed crop production have not fully met expectations and needs. There is still great opportunity for high payoff R & D under the quality maintenance strategy. Some areas that have been neglected deserve more attention, while excessive fine-tuning in some long and well-tilled areas should be reduced. A few areas deserving of continued and/or increased attention are identified below.

- The role of field and storage fungi in seed deterioration needs to be more clearly defined.
- The influence of physiological seed quality on the growth, development, and production of crops needs more rigorous examination; especially, the level of quality that must be maintained to assure that the physiological quality of the seeds planted is not a major constraint in production.
- The incidence of seedborne diseases needs to be minimized to the degree economically feasible.
- Efforts to reduce the incidence and severity of mechanical abuse to seeds need to continue.
- More efficient and effective quality assurance and control procedures and techniques need to be devised and implemented with emphasis on very rapid and portable methods for evaluating seed; especially, methods for assessing the storability of seed lots need to be improved, simplified, and adapted for routine use in management of seed inventories.

Some Additional and/or Key References

Production Environment: Green et al. (1965); Mondragon and Potts (1974); Nangju (1977); Sciumbato et al. (1981); Tekrony and Egli (1985); Whigham and Stoller (1979); USDA (1961).

Mechanical Damage: Atkin (1954); Baskin and Delouche (1971B); Davis (1964); Ellis et al. (1988); Huelsen and Brown (1952); The Ohio State University (1972); Toole and Toole (1960); Wilson and McDonald (1992);

Storage and Packaging: Delouche (1988); Harrington (1957, 1958); Roos (1986).

Drying and Conditioning: Brooker et al. (1992); Kreyger (1972); Vaughan et al. (1967); Welch et al. (1981).

New Approaches and Seed Coat Effects: Duke and Kakefuda (1981); Powell et al. (1984); Rudrapal and Nakamura (1988); Taft et al. (1988).

Quality Upgrading Strategy

The "upgrading" strategy for improvement of seed quality is as ancient as winnowing. Presently, it is especially employed by seedsmen desperate to raise germination just a "few points" to meet certification or trade standards. The strategy is sound. Most seed lots contain defective and low-quality seeds, which, if removed from the "good" seeds, will increase germination a "few points" or even many points. The problem is: how can upgrading be accomplished effectively and economically? The crucial requirements for upgrading seed quality through removal of the defective and low-quality seeds in the population (i.e., seed lot) are: first, there must be some physical difference between the high- and low-quality seeds (Vaughan and Delouche, 1968; Vaughan et al., 1967); and second, there must be some device(s) that can economically separate the high-quality seeds from the low-quality seeds on the basis of their difference(s) (Delouche, 1965; Welch et al., 1981).

Defective and low quality seeds that are visually distinct from the other seeds in the lot, of course, can be separated by hand. Hand sorting of seeds is a common conditioning procedure in developing countries where labor is plentiful and low cost; e.g., insect and mechanically damaged, rotted, and defective seeds are routinely hand-picked from acid-delinted hybrid cotton seeds and other high value seeds in India (Mishra and Desai, 1979; Baig, 1992). However, this is a very infrequently used measure of last resort in the United States and other agriculturally advanced countries where labor is scarce and costly—except in special cases such as the routine sorting of hybrid corn seeds **in the ear** before drying.

Mechanical and electronic devices, however, are increasingly and effectively employed to remove seeds with low germination and vigor from seed lots before marketing and, especially, before coating or subjecting them to treatments to enhance quality. The physical properties of seeds most commonly used in mechanized quality upgrading operations are seed size, density, and color or reflectivity.

Seed Size

Seed size is, perhaps, the most obvious difference among seeds in a population or lot. A relationship between seed size

and seed germination/vigor in a variety or kind has long been recognized and taken advantage of to upgrade seed quality (Churchill, 1989; Hays, 1896). In a paper in the first volume of the Journal of the American Society of Agronomy, Zavitz (1910) argued that farmers should plant only the larger seeds of a kind or variety for crop production. Similarly, Kiesselback (1924) demonstrated a relationship between seed size and productivity in the small grain crops and advocated sieving to eliminate the smaller seeds before planting.

Many other workers have investigated the relationship between seed size and seed quality or performance in many different seed kinds and for different levels of performance, ranging from laboratory germination to productivity and yield (see classified references at the end of this). While the results of these many studies have been generally consistent in showing that seed size and physiological quality are positively correlated, i.e., physiological quality and performance potential generally increase as seed size increases, their practical significance and implications are frequently unclear or ambiguous. This is due primarily to a serious confounding (or confusion) of absolute and relative seed size in many of the studies, especially the older ones, which make interpretation of the results difficult or impossible.

Table 5. Relation of seed physiological quality to seed size in lots of six crop kinds.

Seed Kind/ Quality Factor	Relative Seed Size				
	Largest	2	3	4	Smallest
	%				
Turnip[1]					
Std. Germ.	99a	99a	—	99a	95b
Acc. Aging	87a	82ab	—	76b	74b
Cabbage[1]					
Std. Germ.	94a	—	93a	—	89b
3-Day Germ.	77a	—	68b	—	61c
Wheat[2]					
Std. Germ.	96a	94a	—	89b	80c
Acc. Aging	90a	90a	—	78b	60c
Pearl Millet[3]					
Std. Germ.	86a	82a	72b	54c	44d
Red Clover[4]					
Std. Germ.	83a	80a	79a	64b	52c
Crimson Clover[4]					
Std. Germ.	69c	80a	84a	84a	74bc

[1]From Hanumaiah (1971): turnip seed size ranged from <1/15 to <1/19 inch in width; cabbage seeds size ranged from >1/13 to <1/15 inch in width.

[2]From Delouche (1981), unpublished data, cv. Doublecrop: seed size ranged from >7/64 to <4/64 inch in thickness.

[3]From Bakhoum (1991): seed size ranged from >7+/64 to <5/64 inch in width.

[4]From Vaughan (1962): red clover seed size ranged from >1/15 to <1/22 inch in width; crimson clover seed size ranged from >1/13 to <1/18 inch in width.

Means in rows not followed by the same letter differ significantly at the 5% level of probability (DMRT).

Illustrative data from studies on seed size/quality relationships in the STL are presented in Table 5 for six kinds of seeds. Germination and/or vigor, as manifested in accelerated aging responses and seedling growth rate, increased as relative seed size increased, especially from the smallest to the medium-size class. An exception was crimson clover, for which both the largest and smallest size seeds were lower in quality than those of medium size, an interesting response that was related to the severe weathering of the crimson clover seed lot produced in Mississippi rather than in the Pacific Northwest. The largest seeds were distinctly different in appearance than the other seeds — swollen and darker in color.

In the case of sorghum seed (Table 6), there was considerable variability in the seed size/quality relationship among varieties (lots); but over all of the six varieties (lots), the large and medium-size seeds were significantly higher in germination than the small and unsized seed classes; and the small seeds were significantly lower in germination than the unsized seeds.

Table 6. Percent by weight and germination of seeds in three relative size classes for six cultivars and lines of sorghum. (From Cortes, 1987.)

Cultivar/Line	Relative Size Class	Seed Weight	Germination
		%	%
Redbine 66	Large	9.1	83
	Medium	81.8	85
	Small	9.1	59
	Unsized		78
P954063	Large	13.2	87
	Medium	73.8	88
	Small	13.0	55
	Unsized		80
SC 175-14	Large	6.2	87
	Medium	83.0	85
	Small	10.8	70
	Unsized		83
TX 2536	Large	8.4	73
	Medium	81.6	75
	Small	10.1	32
	Unsized		62
DR-1125 (Cargill Hyb.)	Large	11.0	69
	Medium	83.0	70
	Small	6.0	69
	Unsized		71
BR-54 (Dekalb Hyb.)	Large	24.9	97
	Medium	67.9	95
	Small	7.2	88
	Unsized		93
Means	Large	12.1	83a
	Medium	78.5	83a
	Small	9.4	62c
	Unsized	—	78b

Germination means not followed by the same letter differ significantly at the 0.05 level of probability according to the Student Newman-Keuls' test (SNK).

Among major crops, seed size quality relationships have been most extensively studied in soybeans. While most researchers found that germination and emergence of the larger seeds within a lot were higher than those of the smaller seeds (e.g. Fontes and Ohlrogge, 1972; Burris et al., 1973), absolute and relative seed size are, unfortunately, confounded in many of the studies. For example, Edwards and Hartwig (1971) reported that the rate of emergence in soybeans increased as seed size decreased but the response was related to inherent differences in seed size rather than to differences in relative seed size in populations produced in different environments.

Research of Agronomy-Seed Technology doctoral students P. Aguiar and C. Wetzel, both from Brazil, in the mid-1970's was pivotal in clarifying the seed size and quality relationship in soybean and by extrapolation in many other kinds of seeds. Aguiar (1974) demonstrated that seed size in soybean varieties varied widely among locations (Table 7).

In 1972, seeds of the Bragg and Lee 68 varieties produced in Texas were more than 2/64-inch larger in mean diameter than those produced in South Carolina, while those produced in Louisiana (Bragg) and Mississippi (Lee 68) were intermediate in size. Germination consistently increased as seed size within a variety/lot increased up to the very largest size classes, which made up only a very small percentage of the seeds and consisted mostly of misshapen and/or badly weathered seeds.

Wetzel (1975) took advantage of the availability of three "isolines" of soybeans differing in seed size to examine the relationship between relative size, absolute size, and quality. The medium-size line was the variety Lee while the large- and small-seeded lines were near isogenic lines of Lee. Seeds of the three lines produced at the same location in 1973 were essentially normally distributed with mean sizes as follows: 17.2/64-inch, large seed line; 15.1/64-inch medium seed line; and 13.6/64-inch for small seed line (Table 8). Germination significantly decreased in each isoline as seed size decreased 2/64-inch below the mean and was related to relative rather than absolute or actual seed size. Seeds from the large seed isoline that were 14/64-inch in diameter were relatively small and germinated poorly, while those of the same diameter in the medium and small seed isolines were near the mean size or relatively large and germinated as well as those of even larger size.

On the basis of results obtained by Aguiar as well as from his own extensive studies, Wetzel made some important conclusions on the seed size and quality relationship in soybean:

- Within a soybean seed population, seeds of the mean size

Table 7. Seed size distribution by weight and percent germination by size class for nine lots of three soybean varieties produced in different locations in 1972. (From Aguiar, 1974.)

Variety	Lot No.	Origin (State)	Factor	Seed Diameter (64th-inch)								Mean Diameter 64th-Inch
				11	12	13	14	15	16	17	18	
				% Seeds								
Bragg	2	SC	Seeds	0	5	21	43	24	6	1	0	14.1
			Germ.	—	88bc	90ab	94a	93a	87bc	84c		
	4	TX	Seeds	0	0	0	2	6	32	46	14	16.8
			Germ.				87c	98a	93ab	96a	89bc	
	5	LA	Seeds	0	0	5	21	31	29	12	2	15.3
			Germ.			74b	80ab	86a	86a	84ab	82ab	
Dare	8	SC	Seeds	0	1	8	39	39	12	1	0	14.6
			Germ.		73d	82ab	80bc	87a	86a	75cd		
	10	TX	Seeds	0	1	2	12	37	38	9	1	15.4
					84d	89bcd	87cd	93ab	94ab	96a	96a	
	12	MS	Seeds	0	2	7	24	34	27	5	1	14.9
			Germ.		60bc	71a	72a	70a	68ab	52c	54c	
Lee 68	13	SC	Seeds	1	5	25	52	15	2	0	0	13.8
				71b	92a	93a	95a	94a	93a			
	16	TX	Seeds	0	0	1	3	14	42	33	7	16.3
			Germ.			86ab	90a	84abc	82bc	76c	76c	
	18	MS	Seeds	0	1	3	20	43	29	4	0	15.1
			Germ.		55c	84b	96a	94a	96ab	94a		

Means in rows not followed by the same letter differ significantly at the 0.05 level of probability (DMRT).

Table 8. Seed size distribution by weight and percent germination for each size class for three seed size isolines of soybean. (After Wetzel, 1975.)

Seed Size (64th-inch)	Seed Size Isoline					
	Large Line		Medium Line		Small Line	
	Seeds	Germ.	Seeds	Germ.	Seeds	Germ.
	%					
21	1	92a		—		—
20	2	95a		—		—
19	17	93a		—		—
18	27	90a	1	96a		—
17	23[1]	91a	8	97a	1	95a
16	16	88ab	28	96a	4	97a
15	8	70b	33	93a	18	95a
14	4	54c	20	90ab	87	97a
13	1	40cd	6	86b	26	96a
12	1	36de	2	63c	10	93a
11	1	7e	1	53d	2	87a
10		—	1	9e	1	61b
9		—		—	1	25c
8		—		—		—
Mean Size	17.2		15.1			13.6
Unsized		90		92		92

Means in columns not followed by the same letter differ at the 0.01 level of probability (DMRT).

and larger were higher in viability and vigor than those below the mean diameter.

- Seed viability and vigor consistently and progressively decreased as seed size decreased below the mean size.
- There were no consistent seed quality or performance relationships between seeds of the same dimension among isolines; the relationship was always between seed size within a population (or lot) of seeds in relation to the mean size.
- The smaller, very low quality seeds within a population (isoline) made up such a small percentage of the population that their removal did not substantially improve germination or emergence and had no effect on yield.

Wetzel's conclusions on the seed size and quality relationships in soybeans can be and have been generalized to most kinds of seeds: the relationship between seed size and quality is most consistent within a lot or population of seeds; the larger seeds within a population are superior in terms of germinability, stand establishment, and survival (Wood et al., 1977).

While the relationship between seed size and quality is well established, its significance or implications in modern crop production are not considerable except in some specific cases such as certain vegetable seeds. In former times, when seeds were either not cleaned or only grossly cleaned before planting, the small seeds in lots might have significantly contributed to poor performance. With modern seed-conditioning procedures and technologies, however, the immature, shriveled, and smallest seeds are mostly removed along with the small trash so that further sizing to upgrade germination and vigor is usually not effective or not economically practical.

Grabe (1980), however, pointed out that many farmers still save seeds of small grain crops, such as wheat, for planting and they could significantly improve yields in many cases by keeping only 25-30% of the largest seeds for sowing and marketing the rest with little if any extra cost. This relatively recent recommendation echoes those made early in this century by Zavitz (1910) and Kiesselbach (1924).

Surprisingly little research has been done on "why" the small seeds in a population are generally lower in quality than those larger in size. There is little doubt, however, that some degree of immaturity is involved (Baskin and Delouche, 1971A; Burris et al., 1973).

Seed Density

Density is the physical property most consistently associated with seed germination and vigor (Clark, 1904; Whitcomb, 1936; Delouche, 1986). The relationship is well established and very clear, and it can usually be effectively and efficiently exploited to improve the physiological quality of seed lots. For example, in the case of average current season seed lots (i.e., not carryover seed) with germination 70% or above, the higher-density seeds frequently germinate above 90% with good vigor, while the lower-density seeds might germinate well below 60% with low vigor.

The economics of density separations to upgrade physiological quality of seed lots are strongly influenced by the amount of high-density seeds in the lot and the difference in quality between the high-density "accepts" and low-density "rejects," or, put another way, by the percentage of seeds that has to be discarded to elevate germination/vigor to the desired level (Abidin, 1992).

Density separations are commonly made with aspirators, pneumatic separators, and gravity tables (Vaughan et al., 1967; Welch et al., 1981). The gravity table is, perhaps, the most effective density separator for most kinds of seeds. With proper arrangements for handling the middling fraction from the separation, and/or combined with air separators, the gravity table can significantly upgrade the germination and vigor of many seed lots. It is routinely used in cotton seed conditioning to remove low-density, low-quality seed (Delouche, 1986), and, somewhat less routinely, for the same purposes in conditioning seeds of corn, soybeans, sorghum, wheat, rice, sunflowers, trees (e.g., *Pinus* spp.), and many other field, vegetable, ornamental, and speciality crops, frequently with results as dramatic as those with cotton seed.

Gregg (1969) made perhaps the most exhaustive and definitive study of the association of seed quality with seed density and specific gravity in cotton. He worked with 20 acid-delinted lots of five varieties of cotton. Summary responses are shown in Figure 3. Seed quality increased as bulk density of the seeds increased up to about 44 pounds per bushel. Interestingly, but not surprisingly, the most dense seeds were somewhat lower in quality than those in the next

highest density class. (In many of the reported studies, the very largest and the highest density seeds, which make up only a small portion of the seed lot, were lower in quality than those slightly smaller in size and slightly less dense.) Gregg recommended that cotton seeds less than 42 pounds per bushel be diverted to the oil mill. While this recommendation is not strictly followed in commercial practice, as much as 30% of the lower density seed is discarded during conditioning.

The seed density/quality relationship in cotton has been confirmed and fine tuned by many other workers, especially Johnson et al. (1973), Krieg and Bartee (1975), and Leffler and Williams (1975). Justus et al. (1965) and Johnson et al. (1973) demonstrated that the density of seeds planted had a significant effect on yield of the cotton crop.

Until the early 1980's, the gravity table was employed in soybean seed conditioning primarily to remove soil peds and other dense inert material. About this time, however, work by Assman (1983) and workshops in the annual MSU Short Courses for Seedsmen clearly demonstrated the substantial benefits of gravity table conditioning (i.e. density grading) of soybean seeds in improving both the physiological and physical (appearance) qualities of seed lots, and it began to be widely practiced. Assman determined the benefits of density grading in soybean seed lots for several varieties ranging in quality from low to high. Germination and field emergence increased as seed density (volume weight) increased, with the greatest increases in the low- and medium-quality seed lots (Table 9).

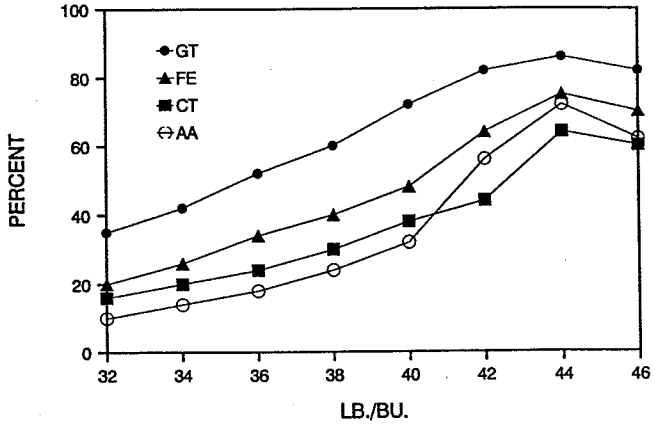

Figure 3. Relation of the bulk density (pounds per bushel) of cotton seeds to germination and vigor. Average 20 seed lots: GT, germination; FE, field emergence; CT, cold test; AA, accelerated aging. (After Gregg, 1969.)

The effectiveness of gravity table conditioning in upgrading seed quality was attributed, in part, to concentration of mechanically damaged and badly weathered seeds in the lower density "reject" fraction. These findings were corroborated in the more recent work of Urisong (1987), who found

Table 9. Effects of gravity table separation on the physical properties, quality, and performance of high, medium, and low quality soybean seeds. (Average of four lots each quality class. (After Assman, 1983.)

				Gravity Table Separate			
		Seed Quality	Original	Heaviest			Lightest
Attribute	Unit	Class	Lot	1	2	3	4
Seeds	%	High	100.0	28	27	29	16
		Medium	100.0	30	28	27	15
		Low	100.0	31	27	28	14
Volume Weight	lb/bu	High	58.0	58	58	58	57.6
		Medium	56.2	57.0	56.8	56.4	53.9
		Low	56.3	57.0	56.6	56.1	53.9
Seed Weight	g/100 seeds	High	14.0	14.9	14.3	13.9	13.2
		Medium	13.4	14.1	13.6	13.1	12.5
		Low	13.6	14.6	13.8	13.1	12.4
Weather Damage	%	High	12 b	8 a	9 a	12 b	19 c
		Medium	19 b	12 a	14 a	20 b	31 c
		Low	21 c	13 a	15 b	22 b	40 d
Mechanical Damage	%	High	9 b	5 a	8 b	11 c	17 d
		Medium	15 c	8 a	12 b	19 d	35 f
		Low	17 b	9 a	15 b	26 c	41 d
Germination	%	High	94 b	97 a	97 a	94 b	90 c
		Medium	81 c	88 a	85 b	78 d	68 f
		Low	72 b	82 a	82 a	71 b	59 c
Field Emergence	%	High	86 b	90 a	89 a	86 b	77 c
		Medium	69 c	78 a	73 b	62 d	42 e
		Low	53 c	68 a	65 b	45 d	20 e

Means within rows not followed by the same letter differ significantly at the 5% level of probability (SNK).

that while germination and emergence generally increased with increasing seed density, final yield was not affected.

Density separations are also very effective in upgrading physiological seed quality in the small grain and cereal crops (Whitcomb, 1936). Flotation separations have long been used in some rice cultures in Asia to remove the low-density, low-quality rice seeds before sowing in seedbeds (Sung and Delouche, 1962). Sung and Delouche (1962), Kamil (1974), and Islam (1976) all found that for U.S. varieties of rice, seeds 1.13 or higher in specific gravity were superior in germination, field emergence, and seedling growth rate to seeds less than 1.13 in specific gravity. Representative results from Sung and Delouche (1962) are in Table 10.

Kamil (1974) and Da Rocha (1975) both reported that plantings from very high specific gravity seeds (i.e., 1.16 and above) produced higher yields per unit area than those from lighter seeds. While Sung and Delouche (1962) showed that most seeds less than 1.13 in specific gravity were removed through proper conditioning with a modern air and sieve machine, they pointed out that in many rice-growing areas in Africa and Asia, most seeds are cleaned only by winnowing before sowing. Substantial benefits could be gained, therefore, by using flotation separation that is traditional in some Asian production areas.

There has also been considerable research and practical interest in the seed density/quality relationship in sorghum. Maranville and Clegg (1977) and, more recently, Cortes (1987) and Goggi (1990), reported that there was a close and consistent relationship between seed density and germination, field emergence, and stand establishment in current crop sorghum seed lots. Cortes separated seeds of several lines of sorghum into specific gravity classes ranging from <1.14 to >1.34 using sucrose solutions and found that germination increased as seed specific gravity increased (Figure 4). There was an especially sharp increase in germination as seed specific gravity increased from 1.22 to 1.26. Goggi (1990) and Goggi et al. (1994) demonstrated rather conclusively that low seed specific gravity or density and low seed quality were

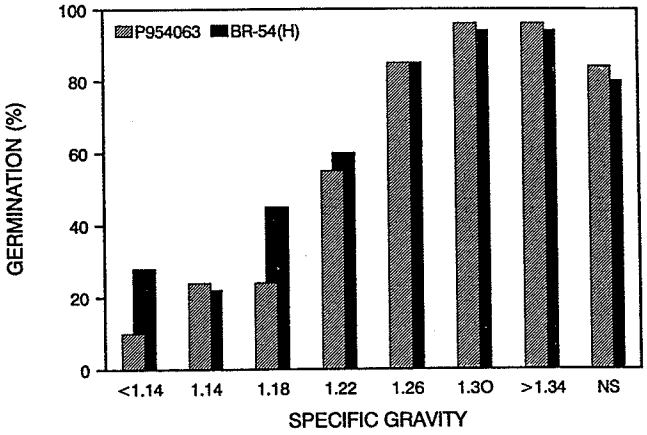

Figure 4. Effect of specific gravity of the seeds on germination of BR-54(H) and P954063 sorghum: NS = not separated. (After Cortes, 1987.)

associated with seed immaturity and field deterioration from weathering.

Seed size and density interact in their association with physiological quality and performance potential. The small-light seeds are lowest in quality while the large-heavy seeds (excluding the very heaviest and very largest) are highest in quality. Interestingly, hardseededness in small-seeded legumes and even soybeans, which contributes to longevity, is associated with small seed size. In crimson and white clover, the hard seeds were concentrated in the small-heavy seeds as indicated from the data in Table 11 from Vaughan (1962). The strong relationship between small seed size and hardseededness in annual clovers has been used to accelerate mass selection of strains with high hard-seed percentages for reseeding purposes (Knight et al., 1964).

Density separation has been used to eliminate or reduce the diseased seeds in a seed lot when they are lower in density than healthy seeds because of premature ripening and other factors associated with the disease. Fezer (1962) reduced

Table 10. Effect of specific gravity of the seeds on germination and 8-day seedling growth for three rice varieties. (From Sung and Delouche, 1962.)

		Seed Specific Gravity						
Variety	Response[1]	<1.0	1.01-1.05	1.06-1.10	1.10-1.13	1.14-1.16	1.17-1.20	>1.20
Belle Patna	GM (%)	56	91	92	97	98	98	97
	PL (mm)	26	34	35	38	40	42	45
	RL (mm)	68	83	79	94	100	108	112
Nato	GM (%)	48	77	86	88	95	93	95
	PL (mm)	16	22	23	27	31	31	32
	RL (mm)	42	49	41	49	56	62	67
Bluebonnet 50	GM (%)	66	83	92	97	100	100	100
	PL (mm)	27	26	33	34	36	40	42
	RL (mm)	70	73	88	88	93	103	114

[1]GM = germination; PL = 8-day plumule length; RL = 8-day primary root length.

Table 11. Effect of the interaction of seed size and density on germination + hard seeds and hard seed percentages in white and crimson clover (avg. of 5 seed lots). (From Vaughan, 1962.)

Seed Size Class	Seed Density Class		
	Light	Medium	Heavy
	%		
	White Clover		
Small	54 (6)	76 (19)	92 (36)
Large	61 (5)	81 (5)	86 (6)
	Crimson Clover		
Small	63 (4)	83 (6)	88 (22)
Large	41 (<1)	65 (<1)	80 (<1)

[1]Numbers in ( ) = hard seeds.

the incidence of loose smut in barley by removing the thinnest and lightest seeds, while Misra et al. (1987) substantially reduced the *Fusarium* spp. (scab) levels in soft red winter wheat by density separation, and Hepperly and Sinclair (1982) separated *Phomopsis* spp. infected soybean seeds from healthy seeds using a density gradient solution, the former being lighter than the latter.

Hydraulic or fluid-type density separations such as used by Cortes and Goggi are very effective and could be more widely used to effect density/specific gravity separations in small lots of high value seeds. With intensive and focussed R & D they could probably be developed into a continuous flow conditioning procedure for large lots of seeds, such as the clay solution and hydrocyclone density separation methods presently used in palm oil processing to separate the kernels from the hulls (Delouche, 1986).

In these connections, Simak (1983) described a very interesting process for separating "filled-dead" from "filled-live" seeds in *Pinus contorta.* He termed the process IDS for incubation or imbibition, actually soaking the seeds in water (I), drying the seeds after soaking to a critical point or for a critical time (D), and separating (S) them with a density separator. The process is based on the fact that dead seeds lose moisture after imbibition much more rapidly than live seeds; thus, in seed lots imbibed then dried for a critical period, a density separation can be made to remove the lower moisture content dead seeds.

While seed density separation is one of the most powerful procedures for upgrading the physiological quality of seeds, it has not been as fully exploited as it should have been. There is need for much focused research to identify seed lots that could be substantially upgraded in quality through density grading and to develop hydraulic or fluid density separation technologies suitable for large-scale application, as noted above.

It is already well known that seed lots of certain crop kinds with reduced quality caused by weathering (e.g., soybean, sorghum, cowpea), drought-induced immaturity (e.g., wheat), and immaturity due to indeterminacy or late tillering (e.g., cotton, peanut, rice), are especially suited for upgrading through density grading. Within the latter group, seed kinds in which immaturity is manifested in an increase in the air or void space within the enclosing seed coat or hulls (e.g., cotton, sunflower, rice) rather than in overall smaller size are exceptionally suited to density grading.

Seed Color

Seed color or coloration, natural and induced, has been associated with physiological quality and performance potential of a variety of seed kinds. Electronic color sorters are widely used in the vegetable seed industry to remove discolored, offtype, and other defective seeds, which upgrades or improves the quality of the seeds marketed. One of the most interesting applications is removal of "bleached" lima bean seeds, which are very low in vigor, from those that are greenish due to retention of chlorophyll in the cotyledons (Pollock and Toole, 1964).

The last operation in peanut seed conditioning before treating and packaging is color sorting to separate seeds with all or a large portion of the thin reddish or brownish "skin" (seed coat) removed during shelling and handling, which is very detrimental to germinability and emergence potential (Bostick, 1985).

Vaughan (1962) and Vaughan and Delouche (1968) showed that seed deterioration in the small-seeded legumes (clovers and alfalfa) was accompanied by a darkening of the seed coat color, and that visual separation of the darker seeds upgraded germination.

Delouche (1965) and dePaul (1991) demonstrated that the dark-colored, inferior seeds in crimson clover and alfalfa, respectively, could be separated with an electronic color sorter resulting in substantial upgrading in germination and vigor.

Boyd (1967) induced color differences in damaged maize and soybean seeds by applying fast green to "stain" and color accentuate the cracks in maize seed and indoxylacetate to accentuate (purplish coloration) the fractures in soybeans, and then separated the mechanically damaged seeds with a color sorter. He also effectively used a color sorter to upgrade physiological quality of weathered cowpea seeds. Illustrative results from the several studies mentioned are in Table 12.

There are obvious limits in using color, glossiness, and similar differences among seeds to upgrade physiological quality. Within these limits, however, much more could be done than is presently being done. R & D in this area need to focus on identifying "natural" and induced seed colors, color hues, reflectivity, even fluorescence (Taylor et al., 1991) that are associated with loss of viability and vigor so that the appropriate separation technologies, which are already well developed, can be applied.

Other Properties

The "Holy Grail" of seed separations would be the efficient separation of non-germinable and low-vigor seeds from

Table 12. Seed quality upgrading through color sorting. (From Boyd, 1967; Delouche, 1965; and da Sie, 1991.)

Kind/Condition	Test[2]	Non-Sorted	Sort Fraction[1] Accepts	Rejects
Maize (4 lots)				
Mech. damage, FG[3]	G	92	96	81
	CT	80	86	64
Soybean (2 lots)				
Mech. damage, IA[4]	G	86	98	36
Soybean (2 lots)				
"Green" seeds[5]	G	84	94	62
Cowpea (2 lots)				
Weathered[6]	G	64	84	59
Alfalfa				
7 lots[7]	G	90	96	79
Crimson Clover				
4 lots[7]	G	78	90	62

[1] Accepts were the "light" color seeds; rejects were the "dark" color seeds.
[2] G = germination; CT = cold test.
[3] Seeds soaked in fast green solution to "color" accent mechanical damage.
[4] Seeds subjected to indoxyl acetate reaction to "color" accent mechanical damage.
[5] Seed lots contained 10-15% seeds that retained greenish color.
[6] Seed lots contained naturally weathered "discolored" (darker) seeds.
[7] Seed lots contained brown and reddish brown seeds indicative of low quality.

the high-vigor seeds without significant loss of good seeds. This efficiency has not yet been achieved although some novel approaches have been tried.

Delouche (1965) briefly subjected seeds of crimson clover to a high level of humidity to induce a slight differential in moisture content between deteriorating and high-quality seeds, as suggested earlier by Vaughan and Delouche (1960), and concentrated the high- and low-quality seeds in "accept" and "reject" fractions obtained by passing them through a high intensity, discharging electric field (so-called electrostatic separation). Matthes and Boyd (1969) confirmed the results obtained by Delouche but pointed out that the seed losses required to achieve the desired upgrading were unacceptable.

Simak (1983) and Bergsten and Lestandes (1983) also took advantage of differential rates of water absorption — fluid and hygroscopic — between dead or deteriorating and viable, vigorous seeds to upgrade quality but with a density rather than electrostatic separator.

The workers who invented the several models of "automatic seed analyzers" (Steere et al., 1981) developed a prototype machine that separated seeds on the basis of differences in current flow patterns of partially imbibed seeds, which is the principle of the "automatic seed analyzer," but it was never commercially developed.

More recently, Krishnan and Berlage (1984) upgraded the germination of onion seeds by applying a magnetic fluid (LIGNOSITE® FML) and using a magnetic separator. The shriveled, immature seeds, which were low in quality, were removed.

In a very interesting recent study, Misra and coworkers (1990) analyzed the "acoustic" properties of soybean seeds and determined that there were consistent differences in acoustic signals related to seed quality.

R & D Emphasis

The search for optimum seed separation technologies, i.e., methods for effectively differentiating among seeds of different quality levels in a population and efficiently removing those of low quality, is still a worthy and justified goal. The great advances in imaging technologies, microelectronics, and computerization offer many leads that need to be closely examined and many avenues that need to be explored, e.g., the variety of radiographic techniques used by Vozzo and coworkers to characterize seed quality in forest species (Vozzo, 1988; Vozzo and Marko, 1994). While the new technologies must be fully exploited, those already well established should not be neglected. Many improvements in both effectiveness and efficiency are needed and possible.

Some Additional and/or Key References

Seed Size: Ahmed and Zuberi (1973); Ahring and Todd (1978); Bakhoum (1991); Carleton and Cooper (1972); Clark and Peck (1968); Copper et al. (1979); Cortes (1987); Dhillon and Kler (1976); Egli et al. (1987); Fezer (1962); Hanumaiah (1971); Hanumaiah and Andrews (1973); Hill et al. (1986); Hoy and Gamble (1987); Kneebone and Cremer (1955); Lawan et al. (1985); Maranville and Clegg (1977); Marcos and Avancine (1983); McFadden et al. (1960); Mian and Nafziger (1994); Pinthus and Osher (1966); Possamai (1976); Robinson (1974); Sivasubramanian and Ramakrishan (1974); Rogler (1954); Smith and Camper (1975); Sung (1992); Vaughan (1962); Vaughan and Delouche (1969).

Seed Density: Baudet and Misra (1991); Bergsten and Lestandes (1983); Brenchley (1923); Delouche (1965); Gutormson et al. (1993); Hall and Lippert (1973); Kasperbauer and Sutton (1972); Lawan et al. (1985); McFadden et al. (1960); Paliwal et al. (1991); (Townsend (1992); Tupper et al. (1971); Vaughan and Delouche (1968); Wattiranggoon (1989).

Seed Color: Deaken (1974); Dickson (1971); Nugraha (1987); Powell and Oliveria (1986); Smith (1940); Starzinger and West (1982); Stewart and Carlson (1932); Tully et al. (1981); West and Harris (1963); Wyatt (1977).

Differential Permeability: Bergsten and Lestandes (1983); Fayemi (1957); Krishnan and Berlage (1984); Souza and Marcos-Filho (1993); Vaughan (1962).

Electrical and Acoustic Properties and Radiographic Imaging: Delouche (1965); Matthes and Boyd (1969); Misra et al. (1990); Vozzo and Marko (1994).

Genetic Improvement Strategy

The limits of quality and performance of a seed kind are established by inheritance. If the inherent performance capa-

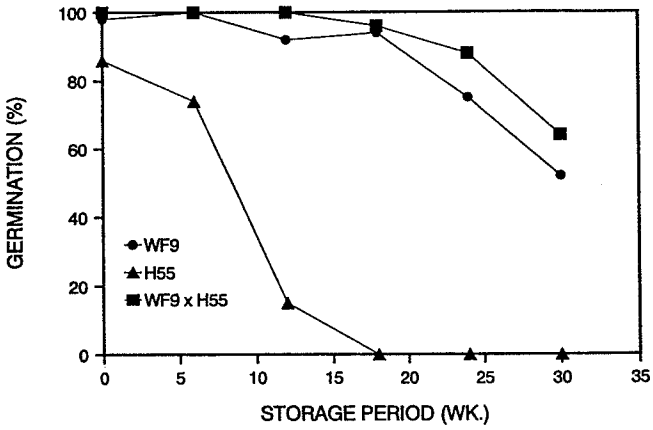

Figure 5. Differences in longevity of seeds of two inbred lines of corn and the single cross hybrid stored at 30 °C and 75% relative humidity. The seeds were produced at the same time and under the same conditions. (After Chang, (1969.)

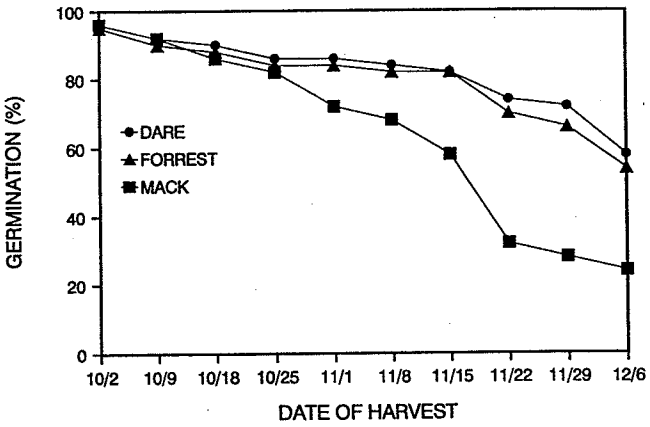

Figure 6. Germination of seeds of Mack, Forrest, and Dare soybeans at weekly intervals after field maturity. (After Lassim, 1975.)

bilities of seeds of modern crop varieties are not adequate, a seed-imposed constraint on gains in productivity has to be accepted, or the inherent and/or physiological capabilities of the seeds have to be elevated or enhanced. Improvements in the qualities and performance of seeds through breeding have been more or less neglected for all but a few crops. In many cases, improvements in yield, yield stability, and produce quality have seemingly been at the expense of the propagative qualities of the seeds. While losses in the qualities of crop seeds during long periods of improvement by man were surely the result of unconscious rather than conscious selection, the consequences in terms of reduced seed capabilities were the same.Fortunately, this situation appears to be changing. Many plant breeders and biotechnologists are very concerned about the longevity, i.e., "shelf life," and stand establishment capabilities of seeds of the crops they are trying to improve and have installed seed quality improvement as a major objective in their R & D programs.

There is abundant evidence of substantial variation in the species and related populations of most crops for seed longevity, the range of environmental conditions for germination/emergence, resistance to weathering, mechanical abuse, and other factors (Kneebone, 1976; Halloin, 1986). Examples from research of our students of differences among varieties of corn and soybeans in seed resistance to field and storage deterioration are shown in Figures 5 and 6.

Where possible, and not to the detriment of essential crop characteristics such as yield and produce quality, superior seed quality and performance traits are being and/or should continue to be transferred to modern varieties. In maize improvement, as an example, breeders have made great strides in improving the capabilities of the seeds for emergence under cool, wet conditions that were considered limiting in earlier times. As a result, the upper boundary of maize production has steadily moved northward (Association of Official Seed Analysts, 1983).

Other examples of the transfer of specific traits from obsolete varieties and exotic strains to modern types include the relatively recent works in soybeans and cotton in which our group has been at the forefront.

Field and Storage Deterioration

Cotton seeds are subject to considerable field deterioration from weathering in the humid, rain-fed U. S. cotton belt, especially since the advent of once-over mechanical harvesting, which results in long exposure of the seeds, as seed cotton, in opened bolls. As mentioned previously, the problem was finally resolved in the mid-1970's by a major shift of seed production to the arid, irrigated western deserts. "After-the-event" R & D have established the hard seed trait in cotton as controlling longevity and weathering resistance (Bragantini, 1984; Patil and Andrews, 1986; Taft et al., 1989) (see Figure 7 and Table 13).

Halloin (1986) showed that selection for weathering

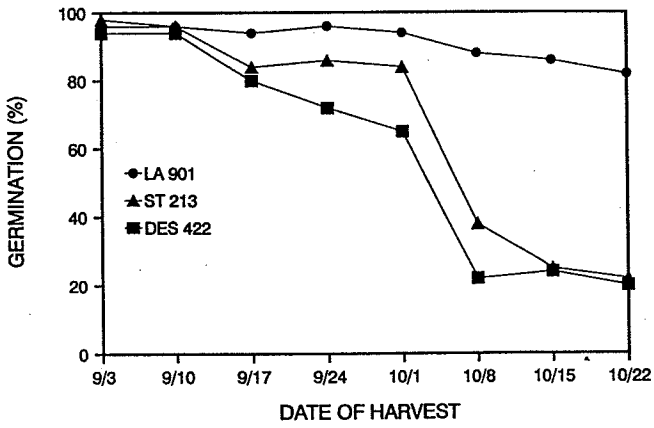

Figure 7. Effect of time of harvest on viability (germination plus hard seeds) percentages of seeds of three cultivars of cotton from same age bolls. (After Bragantini, 1984).

resistance and longevity increased resistance of the seeds to soilborne pathogens in the seeded. Ironically, Christiansen et al. (1960) had demonstrated the significance of the hard-seed trait in cotton as early as 1960, but there was no followup until the early 1980's.

Seeds of modern soybean varieties are inherently short-lived and very susceptible to field deterioration from weathering during the post-maturation, pre-harvest period (Delouche, 1969A). In 1978, Potts et al. (1978) and Potts (1978) reported that the hardseed trait (water impermeability of seed coat common in the forage varieties of former times and in many wild strains) was associated with both resistance to weathering and longevity in storage (Table 14). The moisture content of seeds of the hardseeded strain was remarkably stable compared to that of the softseeded Dare variety even under severe weathering conditions (Table 15).

Stability of moisture content under weathering stress during the preharvest period appears to be the main factor involved in resistance of hardseeded lines to field and storage deterioration for both soybean and cotton (Figure 8).

On the basis of concepts elucidated by Potts and associates, the work on hardseeded soybean lines has continued at MSU (Hairston, 1977; Kilen and Hartwig, 1978; Maxey, 1981; Miranda, 1981; Nugraha, 1987; Keith, 1991; Chuntirapongsa, 1992; Zaidan, 1993), and has been taken up by workers at other institutions in the United States (Calero et al., 1981; Hill et al., 1986; Minor and Paschal, 1982; Moore et al., 1989) and in other countries (Kueneman, 1983; Dassou and Kueneman, 1984; Nugraha et al., 1991). These pro-

Table 13. Effects of storage in three environments for periods up to 12 months on the percent germination and hard seeds in the LA 901 and 16B-7-2 hard seed lines and DES 119 variety of cotton. (From Delouche et al., 1995.)

Line	Storage Period (Months) 0	4	8	12
	%			
	Ambient (Miss. State, MS)			
LA 901	40/58A[1]	66/32B	74/20C	80/16C
DES 119	96A	94A	96A	96A
	20°C—50% Relative Humidity			
LA 901	40/58A	46/50B	48/50B	44/50B
DES 119	96A	96A	94A	96A
	30°C—75% Relative Humidity			
LA 901	40/58A	74/22B	38/8C	0/0D
DES 119	96A	86B	6C	0C

[1]Left or single and right numbers are germination and hard seed percentages, respectively; analysis applies only to hard seeds for LA 901. Statistical comparisons are row means (LSD).

Table 14. Responses of the Dare variety and D-1 hard seed line of soybeans to post-maturation field weathering in 1973 and 1974. (After Potts et al., 1978.)

Harvest Date	Rain	Dare SMC[1]	Dare Germ.	D-1 SMC	D-1 Germ.	D-1 HS	D-1 TVS
		%					
1973							
Oct. 8		21.0	86	16.0	90	8	98
Oct. 14		12.0	89	12.0	60	35	95
Oct. 21	*[2]	15.0	90	11.0	61	31	92
Oct. 29	*	16.0	93	11.0	57	40	97
Nov. 5	*	32.0	72	18.0	39	47	88
Nov. 12	*	17.0	51	10.0	30	62	92
1974							
Oct. 4		15.5	94	10.0	82	15	97
Oct. 12		9.3	92	9.0	50	46	96
Oct. 19	*	9.7	90	8.2	45	46	91
Oct. 26		9.0	88	7.4	35	59	94
Nov. 2		13.1	86	9.1	44	49	93
Nov. 9		10.4	72	8.0	44	48	92
Nov. 16	*	15.8	63	9.2	42	50	92
Nov. 23	*	12.0	50	8.5	46	42	90
Nov. 30	*	14.0	40	10.8	45	43	88
Dec. 7		14.4	32	12.0	46	38	84

[1]SMC = seed moisture content; Germ. = germination; HS = hard seeds; TVS = total viable seeds (Germ. + HS).
[2]Indicates rain of more than 5 mm during the preceding week.

Table 15. Moisture content of seeds of the Dare variety and the hard seed D-1 (D67-5677-1) line of soybean during the post-maturation period in 1976. (After Potts, 1978.)

October Harvest Date	Time	Precipitation (mm)	Moisture (%) Dare	Moisture (%) D-1
8	AM	—	18.2	15.1
	PM		10.9	11.6
10	AM	Trace	15.1	12.8
	PM		13.0	12.2
12	AM	—	15.9	11.4
	PM		11.4	10.0
14	AM	—	9.7	9.5
	PM		12.0	9.7
16	AM	5.5	16.2	9.7
	PM		13.6	9.0
18	AM	—	9.4	9.2
	PM		10.4	7.9
20	AM	1.0	15.8	8.5
	PM		12.7	8.4
22	AM	—	14.2	8.5
	PM		10.7	8.0
24	AM	—	15.2	7.6
	PM		11.3	7.6
26	AM	20.8	22.9	14.4
	PM		22.1	13.7
28	AM	—	15.7	9.6
	PM		12.0	8.8
30	AM	26.3	20.0	12.8
	PM		21.8	11.1
Mean			14.5	10.4

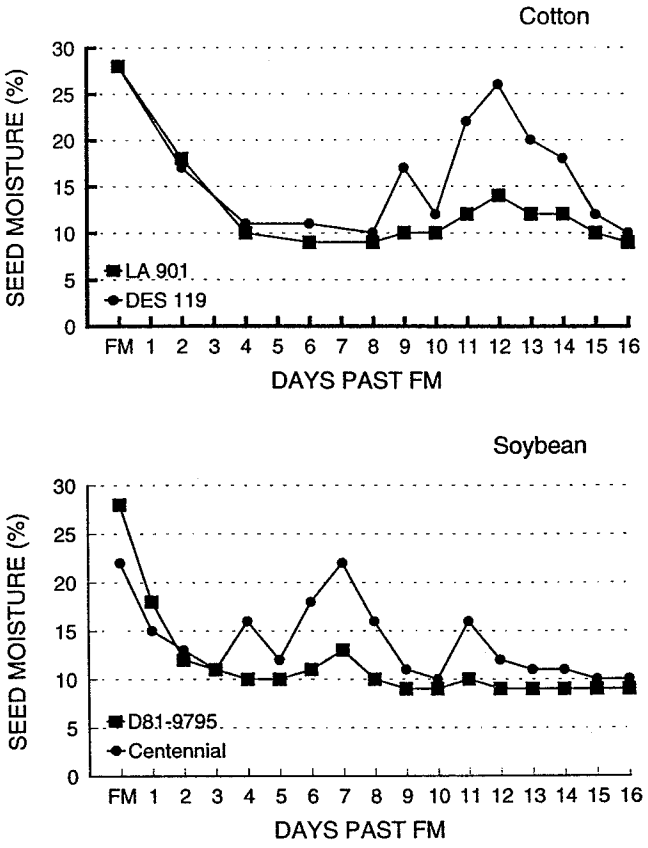

Figure 8. Changes in seed moisture content of hard seed lines and commercial varieties of cotton (1992) and soybeans (1989) during a 16-day period after field maturity (FM), 25-30% seed moisture content. (From Delouche et al., 1995.)

grams have produced families of lines in several maturity groups with excellent longevity, weathering resistance, and agronomic characteristics (Keith, 1991).

The hardseed trait in soybeans occurs in many lines and can be readily intensified and/or transferred to others. It appears to be naturally associated with small-seededness and dark-colored seed coats (Tully et al., 1981; Hill, et al., 1986; Starzinger and West, 1982; Guevara, 1990; Nugraha, 1987). Seeds of hardseeded strains are not only resistant to field and storage deterioration but are also much more resistant to infestation with storage and field fungi than those of soft-seeded varieties (Miranda, 1981; Minor and Paschal, 1982; Guevara, 1990). Jones and Andries (1967, 1969) pointed out that other characters not associated with hardseededness, such as okra leaf and frego bract in cotton, can affect the rate and severity of field deterioration of seeds.

There is a cost associated with use of the hardseeded character and other types of dormancy to improve seed quality through resistance to field and storage deterioration. Emergence is delayed and nonuniform; the incidence of volunteer plants is substantially increased. These problems, however, can be overcome. Better and more effective methods for eliminating or minimizing water impermeability of the seeds before planting would reduce the emergence problems to insignificance and the volunteer problem could be greatly lessened by timely land preparation and crop rotation (Moore et al., 1989; Delouche et al., 1994, 1995).

Stress Tolerance

Many other inherent characters that affect seed performance in important crops have been identified and exploited or should be exploited in breeding programs. In the case of soybeans, the superiority of "smaller" seeds in rate and percent emergence in heavy soils was demonstrated by Edwards and Hartwig (1971), while Grabe and Metzer (1969) first identified the temperature-induced inhibition of hypocotyl elongation in some varieties, which causes an emergence problem for deeply planted seeds at the near optimal temperature of 25 °C.

The superior seed quality of bean varieties with colored seeds has long been noted (Deakin, 1974; Wyatt, 1977; Powell et al., 1984; Powell and Oliveira, 1986). There is substantial evidence that the improved emergeability of colored seeds is related to a slower rate of water absorption as compared to seeds with white or light-colored seed coats, hence less imbibitional damage (Taylor and Dickson, 1987). Pigmented seed coats are also usually thicker and, thus, more resistant to mechanical abuse.

In the small-seeded legumes (*Trifolium* spp.), the hardseed trait increases longevity (Flood, 1978) and confers the reseeding habit, a very desirable trait in annual species (Knight et al., 1964).

There are excellent opportunities for improving the performance of seeds (i.e., emergence) under marginal temperatures and moisture and under stress levels of toxic minerals including salinity. Some progress has already been made as cited previously (Association of Official Seed Analysts, 1983), and in the following additional references section.

The works of Camargo (1982) and Reusche (1982) on differences in response-reactions of sorghum varieties to germination/emergence temperature and moisture supply are illustrative (Figures 9 and 10). There are also needs and opportunities to alter the mechanical and geometrical properties of some crop seeds to improve their resistance to mechanical abuse and emergeability under mechanical impedance in the seeded.

R & D Emphasis

The genetic improvement strategy appears to be very suitable in terms of cost-effectiveness and environmental neutrality. Importation of exotic genes through modern biotechnological procedures makes possible improvements in seed performance over a range of conditions that far exceed the natural variability of the species, e.g., germination under highly saline conditions or exceptionally warm temperatures. Nevertheless, the genetic improvement strategy, even abetted by modern biotechnologies, is relatively long-

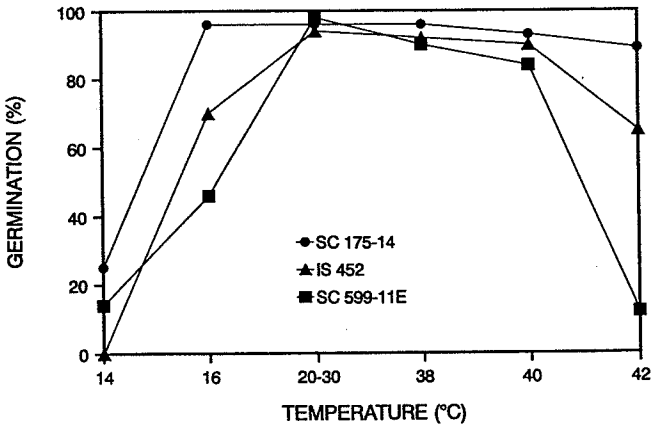

Figure 9. Germination responses of three sorghum genotypes within the temperature range of 14-42 °C. (After Camargo, 1982.)

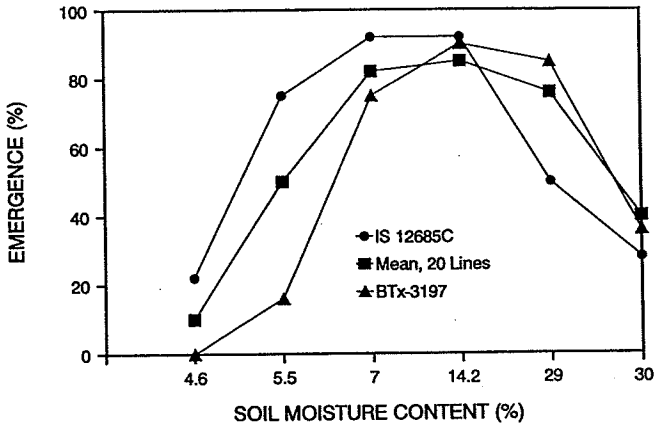

Figure 10. Emergence of two sorghum genotypes as compared to the mean emergence of 20 genotypes at different soil moisture contents. Note: soil moisture scale represents data points and not uniform increments in SMC. (After Reusche, 1982.)

term and the improvements needed in some critical areas might be too long coming onstream. Thus, shorter-term or interim approaches are indicated for which the quality upgrading strategy presented in the previous section and the quality enhancement strategy presented in the next section appear to be very suitable.

Some Additional and/or Key References

Improved Field Performance (Vigor, Emergeability, Stress Tolerance): Bacon et al. (1986); Bird et al. (1979); Bramlage et al. (1979); Buxton and Sprenger (1976); Dickson (1971); Dickson and Boettger (1982); Cal and Obendorf (1972); Fehr (1973); Fehr et al. (1973); Gilman et al. (1973); Jones and Peterson (1976); Kneebone and Cremer (1955); McDonnell and Gardner (1979); Marani and Dag (1962); Mock and Bakri (1976); Pinnell (1949); Rathore et al. (1982); Townswend (1979); Young et al. (1970).

Resistance to Mechanical Damage: Atkin (1948); Davis (1964).

Resistance to Field and Storage Deterioration: Dassou and Kueneman (1984); Flood (1978); Green et al. (1977); Guevara (1994); Halloin (1986); Jones and Andries (1967, 1969); Krul (1978); Kueneman and Wien (1981); Lassim (1975); Lee (1969); Onesirosan (1982); Potts (1985); Rodriguez-Ardon (1987); Scott (1981).

Reseeding Capability: Aswathaiah (1984); Knight et al. (1964); Rampton (1961); Smith (1988); Donnelly (1963); Donnelly et al. (1966).

Quality Enhancement Strategy

When inherent improvements in seed quality are still in the making, and all that can be done to maintain and upgrade seed quality has been done without fully meeting customer expectations regarding performance, what options are left? This is not a rhetorical question. There is a still small but growing segment of the market with requirements for levels of seed performance that are not consistently met by traditional quality maintenance/upgrading procedures. The core of this market segment consists of the seedling/plant and greenhouse cropping industries. Others are joining in, however, including many vegetable growers and even some planters of field crops (Delouche, 1983; Kent, 1984; Sanders, 1985).

High-performance seeds are widely recognized by producers as one of the most cost-effective means of minimizing and/or managing risks. When these are not available, most producers still have the strong perception that things would be much, much better if they could obtain some for planting.

Two present options remain when the quality maintenance and upgrading strategies are fully implemented and the inherent improvements in seed quality are still in the making. These are **quality enhancement** and **seedbed improvement** or optimization. Under both options, quality improvement is in terms of enhanced performance. Seedbed improvements, of course, are not a seed quality improvement *per se*, although their effects mimic quality improvement.

Seed quality enhancement in the current and popular sense refers mostly to osmoconditioning or priming treatments, but its operational meaning and implications are much broader and more pervasive. Essentially and basically, seed quality enhancement involves the elevation or improvement of one or more aspects of seed performance (e.g., germination, emergence) above the level set by inheritance and achievable under natural conditions. It encompasses not only physiological treatments and conditioning (e.g., priming), but also improvements or alterations in physical properties of seeds that enhance plantability and facilitate achievement of optimal stand geometry (e.g, coatings, hulling), and chemical/biological treatments that protect seeds in the soil and regulate germination (e.g., fungicides, plant growth regulators).

Seed Coatings

Seed coatings were developed primarily to facilitate precision planting of crops (Carolus, 1954; Halsey and White, 1980; Larsen, 1962; Miller, 1971; Stuart and Walton, 1981). Precision planting of mainly vegetable crops, made possible by coating/pelleting the seeds to change their shape, has greatly enhanced production in terms of reduced costs and better product uniformity and quality. In more recent times, coatings have not only been used to change the geometry of seeds but also to incorporate or carry materials that enhance performance of seeds and plants that develop from the seeds. Examples are inoculants for leguminous crops (Anon, 1982; Hefley, 1981); lime to modify pH in the immediate vicinity of the seed (Porter, 1978); hydrophilic materials to increase moisture supply (Berdahl and Barker, 1980; Dexter and Miyamoto, 1959; Hefley, 1981; Miyanamoto and Dexter, 1959); activated charcoal (Sharples, 1981); antibiotics for control of bacterial diseases (Ralph, 1976); herbicides (Anon., 1981); and herbicide antidotes or safeners (Peek et al., 1981).

McGinnis and associates (1967) used a three-layer coating on wheat seeds to delay germination and permit full planting of spring wheat in Canada. A calcium peroxide coating has been used on rice seeds to provide oxygen in water seedings (Brandon, et al., 1980; Dadlani, 1992). Donwen (1984) and Rushing (1988) identified and discussed the many other possibilities for additives in seed coatings to enhance performance, protect the seed, and modify germination and seedling growth, some of which are discussed in later sections.

It should be noted that seed coatings do not have to be high-tech and incorporate exotic materials to have very substantial effects on seed performance. Peske (1983) showed that coating soybean seeds with linseed oil, a common hydrophobic material, and/or a captan, a common fungicide, maintained viability of seeds sown in soil too dry for germination or flooded for a period after planting at levels substantially higher than for uncoated, untreated seeds (Tables 16 and 17).

Table 16. Effects of seed treatments on the emergence of Davis and Bragg soybean seed planted in the Marietta sandy loam at moisture contents too low for germination 7 days after adequate moisture was supplied on the 9th day after planting. (After Peske, 1983.)

	Soil Moisture (%)			
	5.33%		4.96%	
Treatment/Coating	Davis	Bragg	Davis	Bragg
	Emergence (%)			
Non-treated	56c	63b	40c	45b
Captan	73a	72a	76a	83a
Linseed Oil	67ab	79a	57b	86a
Silicone[1]	56c	79a	49c	87a
Petroleum Jelly	3d	3c	2d	10c
C.V.	9.9%	9.9%	7.6%	7.6%

[1]Commercial spray.
Means in columns not followed by the same letter differ significantly at the 0.05 level of probability (DMRT).

Table 17. Effects of seed treatments on emergence of Davis soybean seeds planted in two soil types, flooded for a 12-hour period, and replanted in the same soil type at a favorable moisture content for a 7-day emergence period. (After Peske, 1983.)

	Soil Type	
Treatment	Marietta Sandy Loam	Leeper Silty Clay Loam
	Emergence (%)	
Non-treated	47c	49c
Linseed Oil	72a	53b
Captan	47c	49c
Linseed Oil + Captan	69ab	67a
C.V.	3.2%	3.2%

Means in columns not followed by the same capital letter differ significantly at the 0.05 level of probability (DMRT).

The more recent work of Bulan (1991) corroborated and extended Peske's findings and conclusions. Coating soybean seeds with linseed oil or lanolin greatly reduced loss of germinability associated with imbibitional injury under very wet conditions, especially at cooler temperatures, i.e., <28 °C, (Figure 11).

Coating technologies, well developed and widely used in the confectionary and pharmaceutical industries, are being rapidly adapted for use on seeds. Present coatings are being and will be greatly improved, and the range of applications will be greatly extended. Indeed, coating appears to be the essential technology for most types of enhancement treatments. Coatings can regulate the rate of water absorption to avoid injury from too rapid imbibition, extend the longevity of seeds in seedbeds too dry for germination by reducing the rate of increase in seed moisture content, and carry and deliver phytoactive chemicals, biologicals, fungicides, and insecticides in a dustless, environmentally friendly manner. There is no doubt that most seeds produced and conditioned for sale to customers will be coated in some way for some purpose(s), including appearance, by the end of this decade and century (Delouche, 1983; Tyron, 1994B).

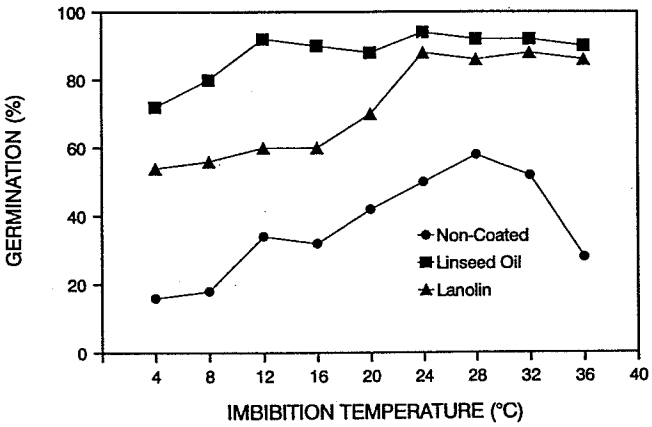

Figure 11. Germination of coated and uncoated Braxton soybean seeds after 12 hours initial imbibition semi-immersed in water at temperatures from 4-36 °C. (After Bulan, 1991.)

Seed Treatments

Conventional seed treatments with fungicidal seed protectants and disinfectants certainly qualify for inclusion under the seed quality enhancement strategy, but they are so well established they do not need further elaboration (Jeffs, 1978; Agarwal and Sinclair, 1987). There are, however, some less conventional treatments that are being exploited and hold very exciting possibilities.

Plant growth regulators, such as gibberellic acid, are applied to seeds by permeation or in coatings to modify germination responses. As early as 1961, just a few years after the "discovery" of gibberellin, Delouche (1961) demonstrated that germination and emergence of centipede grass seeds were greatly accelerated by soaking in 500 to 1,000 ppm gibberellic acid and a slurry coating containing potassium gibberellate (Table 18).

Table 18. Effect of gibberellin and light on germination of centipede grass seed at intervals of 4 and 8 months after harvest. (After Delouche, 1961.)

Time after Harvest (months)	Condition	Gibberellin (ppm) 0	100	500	1000	2000
		%				
4	Dark	27	59	66	86	—
	Light	64	83	84	88	—
8	Dark	52	66	80	82	69
	Light	78	86	89	88	84

Presently, most centipede grass seeds marketed are treated with some sort of plant growth regulator to speed up germination and emergence. Braun et al. (1976) showed that gibberellic acid (GA_3) applied to lettuce seeds released thermodormancy and eliminated the need for light.

More recently, GA_3 is being applied to seeds of semidrawf rice varieties to increase elongation of the mesocotyl and improve emergence (Dunand, 1993). Viera (1991) increased rate of seedling growth (length) by 20 to 40% and mesocotyl length by 5X for the semidrawf Lemont variety with 500 to 750 ppm GA_3 (Table 19). Germination and emergence of bean, soybean, and sugarbeet seeds were improved by soaks in hydrogen peroxide (Smucker and Leep, 1975), while Akenson et al. (1981) improved sugarbeet emergence by treating the seed balls with dilute acid and 1,000 ppm GA_3.

Table 19. Total length and mesocotyl length of 6-day seedlings from seeds of the Maybelle and Lemont cultivars separated into different specific gravity (SG) classes and treated by soaking in GA_3 at several concentrations for 2 hours at 20 °C. (After Vieira, 1991.)

Cultivar/ Treatment	Seed Specific Gravity SG<1.18	Unseparated	SG<1.18
	mm		
	Total Seedling		
Maybelle			
GA_3 750 ppm	187 a	176 a	173 a
500 ppm	161 bc	158 bc	153 b
250 ppm	151 c	159 bc	149 b
Control	140 c	143 c	129 c
Lemont			
GA_3 750 ppm	213 a	202 a	200 a
500 ppm	190 b	184 b	184 b
250 ppm	179 c	175 b	164 c
Control	134 d	127 c	121 d
	Mesocotyl		
Maybelle			
GA_3 750 ppm	12 a	12 a	10 a
500 ppm	12 a	10 b	10 a
250 ppm	10 b	10 b	9 a
Control	6 c	5 c	4 b
Lemont			
GA_3 750 ppm	10 a	10 a	10 a
500 ppm	6 b	6 b	6 b
250 ppm	7 b	6 b	5 b
Control	2 c	2 c	1 c

For each cultivar and measurement, means within columns not followed by the same letter are significantly different at 0.05 level of probability as determined by DMRT.

More recently, GA_3 is being applied to seeds of semidrawf rice varieties to increase elongation of the mesocotyl and improve emergence (Dunand, 1993). Viera (1991) increased rate of seedling growth (length) by 20 to 40% and mesocotyl length by 5X for the semidrawf Lemont variety with 500 to 750 ppm GA_3 (Table 19). Germination and emergence of bean, soybean, and sugarbeet seeds were improved by soaks in hydrogen peroxide (Smucker and Leep, 1975), while Akenson et al. (1981) improved sugarbeet emergence by treating the seed balls with dilute acid and 1,000 ppm GA_3.

Wu (1982) and Harman and Stasz (1987) reviewed the enhancing effects of seed-applied biologicals such as *Trichoderma* spp. on emergence, survival, growth, and development of crops. A strain of *Bacillus subtilus* has been formulated in a seed treatment for peanut (Donwen, 1984; Rushing, 1988) and is now approved for several other crops. Yield increases on the order of 15% are claimed; the selected strain of *B. subtilus* occupies the ecological niches along the root system that would otherwise be occupied by harmful microorganisms. The biologicals are commonly carried in coatings.

The endophytes that live symbiotically in plant species are not a treatment but can act as one. The fescue endophyte, for example, is undesirable when fescue is used for animal feed, but very desirable in terms of insect control when fescue is used for ornamental and recreational purposes (Lacefield, 1983; Hurley et al., 1984). Fescue seeds are marketed with both endophyte-present and endophyte-free guarantees.

Physical Seed Treatments

Brief note should be made of the performance enhancing effects of physical treatments such as scarification and hulling. Andrews (1969) and Bates (1971) doubled yields of green matter from first-year production of arrowleaf clover by scarifying the seeds, which had very high incidences of hard seeds (Table 20). Similarly, Aswathaiah (1984) reported that scarification of common vetch seeds increased green matter production even at reduced seeding rates.

Essentially all bermudagrass seeds in the market are hulled to speed germination and emergence (Ahring and Todd, 1978). Dehulling is especially effective in accelerating and increasing germination of the so-called native range grasses (Anon., 1991A, 1991B).

Table 20. Comparison of laboratory germination and field emergence percentages obtained from five treatments of arrowleaf clover seed. (After Andrews, 1969.)

Treatment	Lab. Germination				12-Day Field Emergence			
	Lot No.				Lot No.			
	1	2	3	4	1	2	3	4
	%							
Commercial Seed	20(77)*	17(81)	34(64)	20(76)	14	24	27	26
Comm./Scarified	93(3)	80(4)	87(6)	78(11)	87	80	75	74
Hard Seed	7(93)	7(93)	12(88)	9(91)	7	5	11	9
Hard Seed/Scarified	96(1)	96(1)	91(1)	95(1)	83	75	87	96
Soft Seed	66(8)	75(7)	84(6)	81(1)	56	75	82	81

*Numbers in parentheses indicate % hard seed.

Permeation of Phytoactive Agents

The report by Meyer and Mayer (1971) that seeds could be safely permeated with chemicals using a nonaqueous medium stimulated much research. So-called dry permeation opened up many possibilities for incorporating phytoactive chemicals in seeds. One interesting approach was to permeate seeds with antioxidants and other longevity "extending" agents to improve storability (Dey and Mukherpere, 1988 Khan and Tao, 1973; Petruzzelli and Taranto, 1985; Woodstock et al., 1983). Others have used dry permeation to incorporate plant growth regulators (Khan, 1977; Nelson and Sharples, 1980), and fungicides (O'Neil et al., 1979). It needs to be noted, however, that the dry permeation technology has not produced the kinds of results and applications initially envisioned, i.e., results have been disappointing.

Avoidance of Stress Injury

Imbibitional injury, or imbibitional chilling injury, has been established as a major trauma for certain kinds of seeds (Christiansen, 1964; Christiansen and Thomas, 1971; Pollock and Toole, 1966; Bramlage et al., 1978; Powell et al., 1984). Several methods have been developed and exploited to avoid imbibitional injury, hence, to enhance performance under conditions favorable for imbibitional injury.

Seeds at moisture content above about 13% are resistant to imbibitional injury, so adjustment of seed moisture content to the safe zone is one of the main procedures for avoiding injury (Cal and Obendorf, 1972; Chen et al., 1983). Several seed companies have developed proprietary "moisturizing" processes and offer "moisturized" bean and pea seeds in certain markets.

Priestly and Leopold (1986) and Bulan (1991) coated soybean seeds with lanolin and linseed oil, respectively, to reduce the rate of imbibition of soybean seeds and avoid injury (see Figure 11).

Some results from the works of Castillo (1990) and Velloza (1991) illustrate the interaction of factors in the imbibitional injury syndrome (Tables 21 and 22). In the case of soybeans, imbibitional injury, manifested as loss of germinability, decreased as seed size decreased and imbibitional temperature and seed moisture content increased. There was little if any imbibitional damage under any conditions when seed moisture content was 13% or higher. Similarly, imbibitional injury in cowpea decreased as seed moisture content and temperature increased. Differential response of varieties appeared to be related to seed coat characteristics rather than seed size.

Table 21. Effects of seed size, initial seed moisture content, and imbibition temperature on germination of seeds of three isolines of soybeans imbibed for 12 hours half-immersed in water in petri dishes. (After Castillo, 1989.)

Factor	Germination
	%
Seed Size (Isoline)	
Small (L-Sml)	81 A
Medium (L-Med)	73 B
Large (L-Lge)	61 C
Imbibition Temperature (°C)	
30	76 A
20	71 A
10	66 B
Initial Seed Moisture Content (%)	
4	46 C
8	70 B
13	93 A

Means within as column for each factor not followed by the same capital letter differ significantly at the 5% level of probability according to DMRT.

Table 22. Effects of initial seed moisture content, imbibition temperature, and variety on the germination of seeds of cowpea imbibed for 12 hours half-immersed in water in petri dishes. (After Velloza, 1991.)

Variety/Seed Size	Initial Seed Moisture Content (%)	Imbibition Temperature (°C)		
		15	25	35
		%		
MS Cream (Small)	4	1 Ba	10 Aa	5 Ca
	8	9 Bb	72 Aa	74 Ba
	12	77 Ab	73 Ab	98 Aa
MS Pinkeye (Medium)	4	52 Ab	64 Ba	69 Ba
	8	44 Bc	62 Bb	78 Aa
	12	55 Ab	86 Aa	81 Aa
MS Bunch Purplehull (Medium)	4	11 Bc	74 Ba	55 Cb
	8	28 Bb	83 Aa	73 Ba
	12	79 Ab	93 Aa	92 Aa
Brown Crowder (Large)	4	2 Bb	66 Ba	74 Ba
	8	18 Bb	93 Aa	92 Aa
	12	95 Aa	99 Aa	97 Aa

For each cultivar, means within columns not followed by the same capital letter and means within rows not followed by the same small letter are significantly different at the 5% level of probability (SNK).

Priming/Osmoconditioning

As already mentioned, seed quality enhancement is usually considered as synonymous with priming and osmoconditioning, although it is clear from the previous discussion there are many quality enhancement procedures that do not involve hydration/dehydration or osmoconditioning. Kotowski (1926) was among the first to demonstrate the beneficial effects on germination and emergence of seed hydration in salt solutions.

Hegarty (1970) reported on the possibility of increasing field establishment of sweet corn and carrot by seed hardening, i.e., hydration/dehydration treatment.

Heydecker and associates (Heydecker, 1974; Heydecker and Higgins, 1973; Heydecker and Gibbins, 1978) developed the osmoconditioning system and used the term "priming" for osmoconditioning and related procedures. More recently, Eastin (1991) developed a proprietory solid matrix priming system (SMP®) as opposed to the usual liquid systems.

Cull (1988) defined seed quality enhancement (priming) in terms of expectations. The expectations include at least one, but usually several, of the following attributes: higher percent germination; increased rate of germination and emergence; increased seedling vigor; higher percent germination and emergence under various stresses and marginal conditions; higher percent productive plants. Cull pointed out that all of the expectations of enhanced performances save one, i.e., increased percent germination, are directly related to the seed quality attribute termed vigor. This is not surprising because quality enhancement is applicable only to germinable seeds just as vigor has meaning only in terms of the germinable seeds in the lot. Since quality enhancement essentially improves vigor, i.e., "invigorates" the seeds, the strategy makes sense only when the level of seed quality achievable through deployment of the other available strategies still does not satisfy consumer expectations regarding performance.

The general principles of priming or osmoconditioning are well known: seeds of the highest quality (usually density graded) are hydrated up to a high level, usually just lower than the critical level of hydration for germination. The hydrated seeds are held at a cool temperature for several days then seeds are planted in the hydrated condition or dried back to normal air-dry moisture content for marketing.

Priming with nutrient solutions increased the rate of germination and emergence of tomato in cool soils (Alvarado and Bradford, 1988). Priming, especially the osmoconditioning species, promoted emergence of watermelon seeds in cold soils for winter season production (Sachs, 1977); improved stand establishment of carrot seeds (Szafirowska et al., 1981); increased the rate and percent emergence of herbage grasses under suboptimal temperatures (Adegbuyi et al., 1981); accelerated emergence of soybean seeds at temperatures below 10 °C (Knypl and Khan, 1981); reduced the time for emergence of parsnip (Gray et al., 1984); accelerated emergence and reduced imbibitional chilling injury in peanut (Fu et al., 1988); and improved germination and emergence of pepper (Bradford et al., 1990).

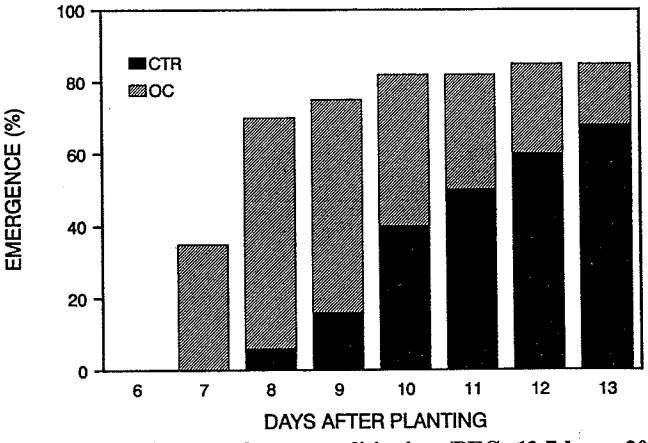

Figure 12. Influence of osmoconditioning (PEG -12.7 bars, 20 °C, 6 days) on the rate and percent emergence of Redlan sorghum at 15 °C (CTR=control; OC=osmoconditioned). (After Santipracha, 1985.)

Khan et al. (1980/81) found that osmoconditioning lettuce seeds in the dark induced dormancy, which could be released by gibberellin. Hydration/dehydration pretreatment of seeds of eggplant and radish reduced loss of viability under accelerated aging conditions and increased longevity in normal storage (Rudrapal and Nakamura, 1988).

The results obtained by Santiprachia (1985) from osmoconditioning sorghum seeds are typical of the enhancement effects of priming and GA_3 treatment on germination and emergence at suboptimal temperatures (Figures 12 and 13). Goggi (1990), however, showed that density grading was more effective in improving the performance of sorghum seed than priming (Table 23). Indeed, priming eroded the beneficial effects of density grading. Nevertheless, priming is, as recently pointed out by Tyron (1994A), a powerful sales and management tool that will be increasingly applied in the years ahead.

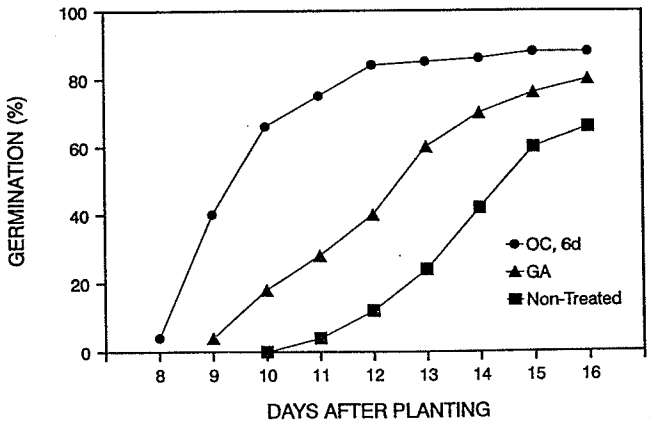

Figure 13. Influence of osmoconditioning (OC) and GA_3 (gibberellin) treatment on the rate and percent emergence of Martin sorghum at 15 °C. (After Santipracha, 1985.)

Table 23. Effects of seed specific gravity (SG) and priming (P) treatments on emergence, growth and development of sorghum. (After Goggi, 1990.)

Seed Treatment	FE[1] 4d	FE[1] 10d	Green[1] Wgt.	Panicle[1] Exsertion
	------- % -------		g/plot	%
Control	17b	55b	2644c	35b
High SG	47a	71a	4217a	56a
High SG + P	42a	65a	3801b	54a

[1]FE = field emergence at 4 and 10 days; green weight at 45 days; % panicles exserted on Aug. 22.
Means in each column not followed by the same letter differ significantly as determined by DMRT.

High Protein Content

Seed and seedling vigor in the small grains is associated with protein content of the embryo (Ries and Everson, 1973), which can be increased by high nitrogen fertilization (Garay, 1975) and may be associated with the seed size effects reported by Grabe (1980).

Exotic Treatments

The area of seed quality enhancement has many exotic approaches. Pittman (1970, 1977) has published many papers on the beneficial effects of magnetism on seed germination and seedling growth. Many other treatments involving various sorts of radiation have been offered, but without consistent results.

Breakthrough

Sanders (1985), in an article on the "boosting" of vegetable seeds, discussed the changing concepts and concerns regarding seed quality. Early in the century, the main emphasis was on variety and the seed suppliers delivered varietally pure seed. Subsequently, the emphasis and concern shifted progressively to "good germination," freedom from disease, uniform size for precision planting, high vigor, and presently, enhancement, which Sanders termed the biggest breakthrough.

Although the methodologies and technologies for enhancement are still in the development stage, most major vegetable seed companies offer enhanced quality seeds of a few select kinds (e.g, tomato, pepper, carrot) under a variety of trade names. The market for enhanced seeds will continue to grow, particularly in the specialty areas, and the number of suppliers will increase.

While the concept of seed quality or performance enhancement has been mostly applied to vegetable seeds, some breakthroughs into agronomic crop seeds (e.g., cotton: rice, the gibberellin treatment of seeds of semidwarfs is enhancement) can be expected in the next few years. The enhancement strategy will be aggressively exploited as the high-tech, high-priced transgenic varieties come into full stream to elevate seed performance as near to expectations of the customer/planter as possible. In time, it will be as routinely deployed as the other strategies for improving seed quality.

Some Additional and/or Key References

General: Delouche (1983); Heydecker and Coolbear (1977); Heydecker et al. (1975).

Osmoconditioning or Priming: Adegbuyi et al. (1981); Armstrong and McDonald (1992); Bradford et al. (1990); Bradford et al. (1988); Eastin (1991); Fujikura et al. (1983); Heydecker (1974); Heydecker et al. (1973); Khan et al. (1980/81); Khan et al. (1984); Pandey (1988); Sanders (1985); Sundstrom (1993); Szafirowska et al. (1981);

Hydration/Dehydration, Nutrient Solutions, and Moisturization Treatments: Aschermann-Kock et al. (1992); Bulan (1991); Bramlage et al. (1978); Chen et al. (1983); Christiansen (1964); Duke and Kakefunda (1981); Ells (1963); Fu et al. (1988); Goldsworthy et al. (1982); Hegarty (1970); Kathiresan and Gnanarethinam (1985); Kotowski (1926); Peske (1983); Pollock and Toole (1966); Rudrapal and Nakamura (1988); Rumphan (1986); Saha et al. (1990); Tully et al. (1981); Velloza (1991); Woodstock and Tao (1981);

Coatings: Anonymous (1982); Brandon et al. (1980); Dadlani et al. (1992); Delouche (1983); Dexter and Migamoto (1959); Hwang and Sung (1991); Khan and Taylor (1986); Porter (1978); Priestly and Leopold (1986); Rushing (1988); Sundstrom (1993); Westcott and Mikhelsen (1980);

Hulling/Scarification/Heat: Ahring and Todd (1978); Andrews (1969); Bates (1971);

Plant Growth Regulators/Phyoactive Chemicals/Permeation: Akenson et al. (1981); Braun et al. (1976); Khan (1977); Khan et al. (1984); Kotowski (1926); Meyer and Mayer (1971); Nelson and Sharples (1980); O'Neill et al. (1979); Rushing (1988); Smucker and Leep (1975);

Seeds As Delivery System: Anonomyous (1982); Brandon et al. (1980); Dadlani et al. (1992); Delouche (1983); Peek et al. (1981); Westcott and Mikhelsen (1980).

Biologicals: Elad et al. (1982); Gustafson, Inc. (1993); Hurley et al. (1984); Lacefield (1983); Wu (1982);

N Fertilization for Seed Production: Garay (1975); Ries and Everson (1973).

Electrical Treatment: Pammenter et al. (1974).

Magnetism: Pittman (1970, 1977);

Summary: Seeds—The Delivery System

From the beginning of crop agriculture, seeds have functioned as the basic propagation unit. Much later, their role as reservoir and carrier of the inherent complement of plants was recognized and exploited — like begets like. In the bio-

logical revolution beginning to engulf agriculture, seeds will be the main delivery system for the innovations and products of biotechnology, and the carriers of crop protection and phytoactive chemicals and biologicals rigorously targeted to minimize environmental effects (Delouche, 1983; Kent, 1984). Great values will be, and are being, added to seeds as a result of the products to be delivered and/or carried into the cropping cycle; values that are lost when the seeds fail to perform in the manner expected.

High seed prices and high expectations of seed users have placed, and will continue to place, great demands on seed suppliers for seeds as near fail-safe as feasible. The conceptual framework for seed quality R & D and the several operative strategies for improving the capabilities and performance of seeds discussed in this bulletin provide the means for meeting many of the expectations of seed users. Undoubtedly, other strategies and/or other means will be needed and will surely be forthcoming.

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