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SEED GERMINATION

James C. Delouche[1]

Germination is the crucial and final event in the life of a seed. It represents both the fulfillment and the completion of the basic function of seed - propagation. Seed - to be sure - have other functions in modern agriculture. They are the main mechanism by which improvements genetically engineered into plant populations are transmitted from one crop generation to another. They also function very efficiently as a convenient means of distributing plant populations throughout areas of adaptation. The latter two functions, however, are wholly dependent on germination. A seed that has lost its capacity for germination can neither transmit genetic improvements nor function in the distribution of desirable plant populations from one place to another.

Seed are produced to propagate crops and other desirable plant species. A substantial portion of the operations and activities involved in seed production and supply are designed to maintain, protect, and/or enhance the propagative value of seed, i.e., capacity to germinate. Seedsmen, therefore, should have a good understanding of the germination process and its vulnerabilities.

Germination is the resumption of active growth of the embryonic axis in seed. The meaning of this definition will be clearer after a brief review of the essential events involved in seed formation and development.

Seed Formation and Development

At some point in the life cycle of annual plants or the seasonal cycle of perennials, the balance of physiological processes shifts from growth to reproduction. Reproductive organs are initiated, develop and mature. Certain cells within the male and female organs undergo meiosis and produce male and female gametes with a reduced chromosome number, i.e., one chromosome from each pair. The stamen which is the male organ produces pollen grains which carry the sperm or male nuclei. The pistil or female organ consists of an ovary, style and stigma. The ovary contains ovules within which the female or egg cells are situated - one

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egg cell per ovule. In angiosperms two other cells - the polar nuclei - participate in the overall reproductive act. A pollen grain is transferred from the anther to the stigma of the pistil. It germinates and produces a tube which grows down through the style and into the ovary and to an ovule. One sperm nuclei from the pollen tube fuses with the egg cell while a second nuclei fuses with the two polar nuclei in the ovule. This double fertilization is characteristic of the angiosperms or flowering plants. (See Figure 1).

Following fertilization the ovary develops into the fruit (e.g., soybean pod) while the ovules develop into the seed (e.g., seed within the pod). The fertilized egg cell divides, multiplies, develops and differentiates into the embryo with 2N chromosome number (one of each pair from the female and male parents). The fertilized polar nuclei develop into the endosperm. The seed coat or covering is derived from maternal tissue - the integuments of the ovule, plus, in some cases, accessory tissues such as the pericarp (fruit coat) and hulls.

The embryo reaches full development and ceases to grow. Moisture content of the maturing seed continues to decrease and food reserves continue to accumulate. Physiological maturity of the seed is attained, i.e., maximum dry matter accumulation, and dehydration of the seed continues until an equilibrium is established between the seed and the relative humidity of the field or storage environment. During seed formation the endosperm develops and constitutes a major portion of the seed in some species, e.g., the starchy portion of a corn kernel. In other species the endosperm develops to a point and is then "reabsorbed" with its "food storage" function taken over by the cotyledons - organs of the embryo.

The events outlined above culminate in the formation of a mature seed. The seed is very dry - 10 to 14% moisture content. Dehydration of living plant tissue to this degree - and even lower - is unusual. The dehydrated condition of seed is a major factor involved its remarkable longevity and resistance to environmental stresses.

Components of Mature Seed and Their Functions

The mature "seed unit" consists of three essential components: a seed covering, storage or supporting tissue, and an embryonic axis in an "arrested" state of development (Figure 2). Each of the three components of the seed has essential roles and functions. The seed covering has two functions: a protective function and a regulatory function. The seed covering maintains a "sterile" condition inside the seed (ideally), and protects the seed against the invasion of external micro-organisms, and mechanical abuse. Seed with fractured seed coverings are much more susceptible to storage fungi and seed rotting organisms in the soil than those with intact seed coverings. In terms of protection against mechanical abuse, a seed with a thick, somewhat elastic seed covering withstands greater mechanical force than one with a thin, brittle seed covering.

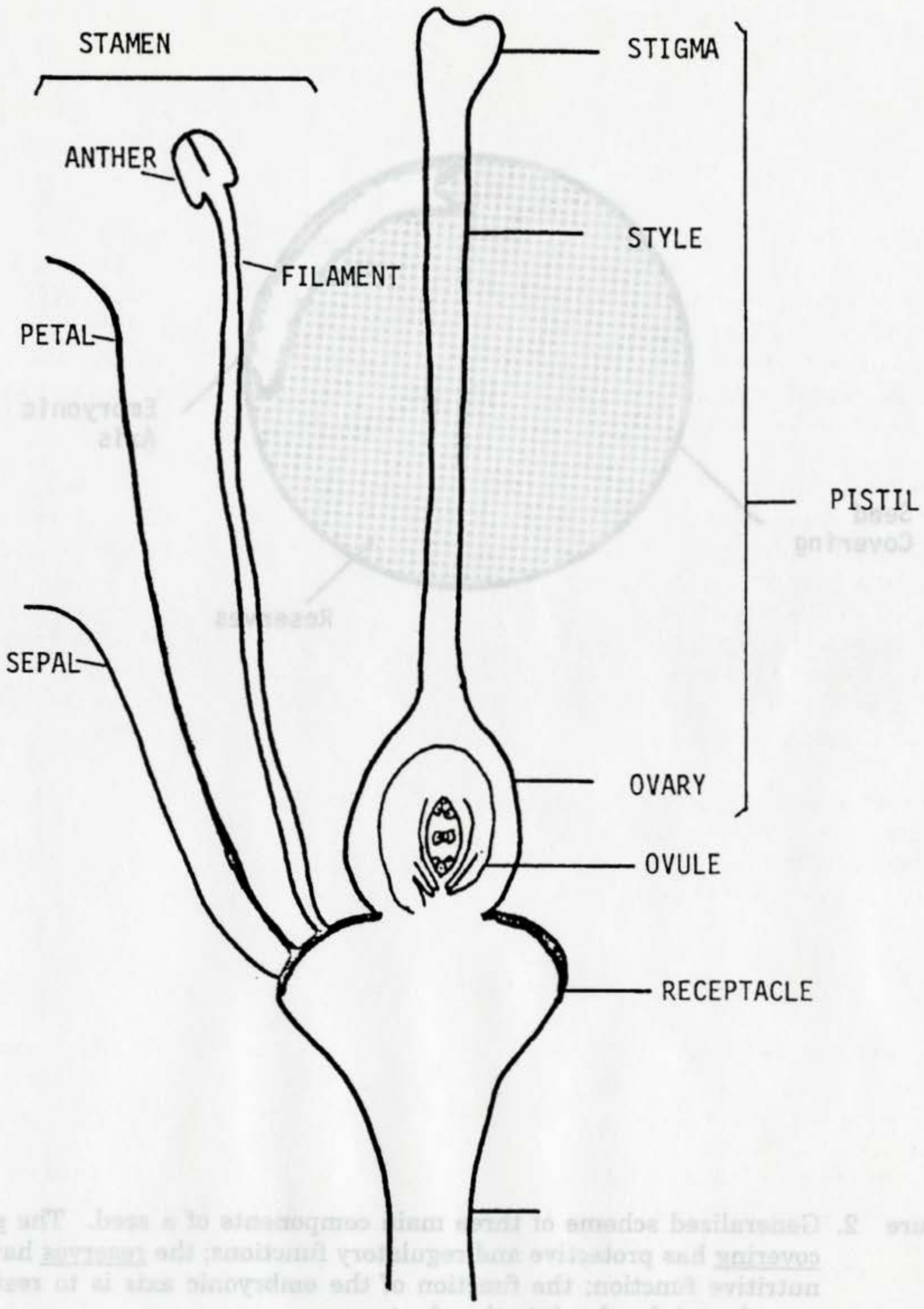


Figure 1. Cut-a-way view of a typical perfect flower.

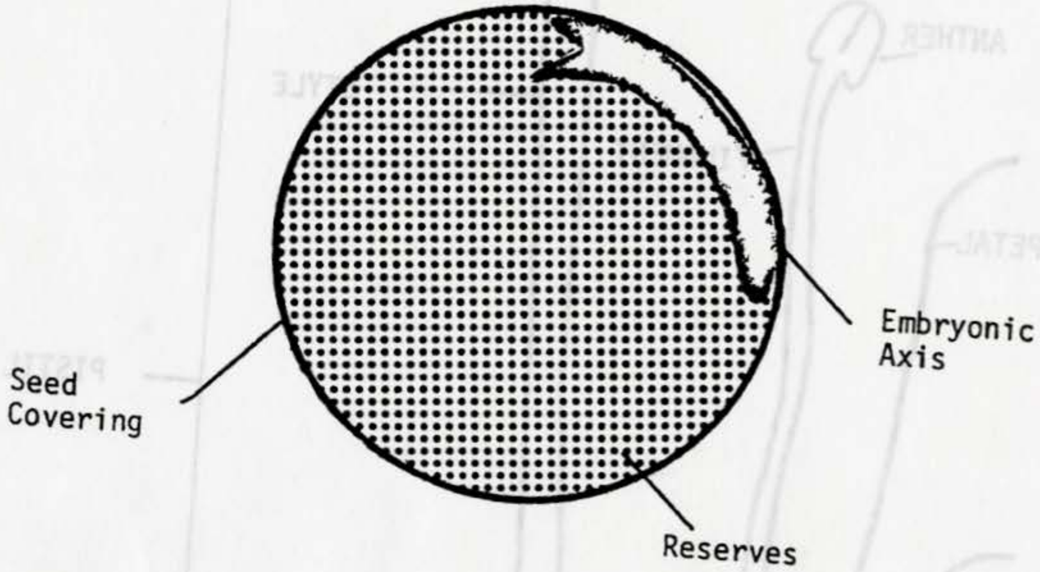


Figure 2. Generalized scheme of three main components of a seed. The seed covering has protective and regulatory functions; the reserves have a nutritive function; the function of the embryonic axis is to resume growth and develop into the plant.

The seed covering regulates the rate of absorption of water - vapor and liquid - and oxygen. Seed always absorb water more rapidly with the seed covering removed (or ruptured) than when it is intact. The reduction in rate of water absorption imposed by the seed covering reduces the magnitude of imbibitional stresses that develop as the "wetting front" moves into the embryonic tissue, thus minimizing tearing of the tissue. The water absorption regulatory function is also involved in dormancy mechanisms. In some species the regulation is extreme - the seed covering is completely impermeable to water (hard seed). In other cases regulation of the rate of water absorption by the seed covering slows the germination process which can be advantageous or disadvantageous depending on the circumstances. A restriction on rate of oxygen absorption imposed by the seed covering is believed to be involved in dormancy in many species, especially species of the grass family. The seed covering, therefore, ultimately regulates germination itself through its regulation of water and oxygen absorption.

The supporting or reserve tissue of seed - endosperm, cotyledons or perisperm - contains starch, proteins, fats and oils, minerals, and other substances. During germination these materials are broken down to provide the energy, "building blocks", and other nutritional materials required to support the resumption of active growth of the embryonic axis. *The function of the embryonic axis is, of course, resumption of active growth leading to the development of a seedling.*

The mature seed dries naturally or is dried artificially to a moisture content of 8-13%. This level of hydration (moisture content) is extremely low and can - at best - support only a maintenance level of activity, deteriorative processes, and physical-physiological changes involved in the "loss" of dormancy. Growth of the embryonic axis ceased prior to the time physiological maturity was attained which - it should be recalled - occurs while seed moisture content is still very high, 30 to 60% depending on the species.

Germination can be considered as a complex of physical and physiological processes which result in the resumption of active growth of the embryonic axis. Physiologists and biochemists usually consider germination as complete when the radicle or root tip ruptures the seed covering and becomes visible. Seed technologists and crop scientists, however, are interested in seedling development so their definition of germination encompasses both the resumption of active growth and early seedling development.

Resumption of active growth of the embryonic axis requires the availability of several environmental factors and conditions.

Requirements for Germination

The basic requirements for germination of seed are moisture, a favorable temperature, and oxygen.

Moisture

Moisture is required for rehydration of the seed to levels that can support greatly increased respiratory activity, the breakdown of complex reserve materials such as starch, fats and oils, and proteins into simple, mobile, and usable forms, and the synthesis of new materials for growth. The moisture or water must be available in the liquid phase. Seed cannot absorb enough water vapor to bring moisture content high enough to support completion of the germination process.

The liquid water required for germination is normally supplied by the media in or on which the seed are planted - soil, peat, blotters, etc. The absorption of water by a seed essentially involves a special type of diffusion called imbibition. Water - or other mobile material - move from a place or area where it is high in concentration (purer) to an area where it is lower in concentration (less pure) by diffusion until an equilibrium is established, assuming, of course, there are no barriers to such movement. The water in a seed at 10-13% moisture content is not very concentrated - it is very impure. It is much lower in concentration than the water in a moist blotter, damp peat, or even relatively "dry" soil. The net movement of water, therefore, is from the media (soil, peat, blotter, etc.) into the seed. As mentioned above the initial stages of water absorption by a seed are most physical. They are the same whether the seed is alive and germinable, alive and nongerminable (dormant), or dead.

As water continues to move into the seed, the cells rehydrate and begin to develop a pressure - a bit like the pressure which develops as a tire is inflated. Rate of water absorption slows down as the internal pressure - hydrostatic pressure - increases. A point is eventually reached where the hydrostatic pressure in the seed cancels out any remaining difference in diffusion pressure between water in the media and seed, and an equilibrium is established. The seed is "fully" imbibed. The "fully imbibed" condition roughly corresponds to the seed moisture content required for gemination.

The seed moisture content required for germination varies among the species. A seed of a species of the grass family - grasses, cereals, small grains, etc., must attain and maintain a moisture content of 30-40% in order for germination to proceed to the point where active growth is resumed. Other kinds of seed, because of differences in chemical composition, require higher moisture contents for germination - 50 to 60% for cotton, soybean, and peanut seed.

Earlier, the statement was made that water absorption by seed involves a special type of diffusion called imbibition. Imbibition is characterized by a swelling of the imbibing material (e.g., seed) and the intake of relatively great amounts of water in relation to the initial volume and dry weight of the imbibing material. The colloidal materials in seed have a great affinity for water and swell as they become hydrated. Imbibition is also characterized by the production of heat.

The rate of water absorption by seed is affected by several factors: the permeability of the seed covering to water; initial moisture content of the seed; temperature; the relative concentration or purity of water in the seed and in the media; the extent of forces binding water to the media; the extent of contact of the seed with the water supply; and the chemical composition of the seed. The coat or covering of a seed generally restricts the rate of water absorption to some degree, which is desirable. In some cases, however, the seed covering is impermeable to water, and no water can be absorbed. This condition is certainly undesirable at planting time.

Other factors being equal, the rate of water absorption by a seed increases as temperature increases (within a "biological" range), the initial moisture content is lower, the area of the seed in contact with water is larger, and the difference in concentration of water in the media (high) and seed (low) is wider.

Although seed have a great "capacity" for absorption of water, several field conditions can reduce the availability of water to the extent that the critical seed moisture content for germination cannot be attained. Lack of rain or evaporation during seed bed preparation can result in a low supply of moisture in the soil through the planting depth. Under such conditions rate of water absorption, hence, germination can be slowed down considerably. If the soil moisture is still lower, the seed might be able to absorb only enough water to increase moisture content to 20 to 25%, which is not enough for germination. Until the soil is resupplied with moisture by rain or irrigation, the seed are in effect "stored" in the soil at a high moisture content and often at high temperatures. If this "storage" period is sufficiently long, the seed will deteriorate, be attacked by seed rotting organisms, and die. Situations such as this are often responsible for stand failures in late planted soybeans. The soil is too dry to supply enough water for the seed to germinate but they do increase in moisture content and swell. The soil temperature at planting depth can in Mississippi range from 80°F during the night to over 100°F during the day. Soybean seed do not live long under such conditions.

Planting seed in the fertilizer band reduces the availability of water to the seed because the fertilizer reduces the concentration of water in the band zone.

Oxygen

A second general requirement for germination of seed is a supply of oxygen. Oxygen is needed for a great increase in respiratory activity to provide energy to drive the germination process. Since the atmosphere has an abundance of oxygen, it becomes limiting for germination only when its availability to the seed is blocked or impeded by some environmental factor or seed condition. Excessive moisture in the soil or other media displaces oxygen in the pore spaces and can reduce its availability to the seed below the threshold level. Many kinds of seed die and ferment in soil that is water logged for more than 2 or 3 days. The covering or coat of some kinds of seed imposes dormancy on the seed because it restricts absorption of oxygen.

A few kinds of seed such as those of rice and some aquatic plants can germinate submerged in water - a condition that severely limits or excludes oxygen.

Favorable Temperature

For each kind of seed there is a range of temperature within which the germination process can proceed to completion in a reasonable period of time if it is not blocked by dormancy. The classical work on seed germination defines three cardinal points along the temperature range for germination of a species. These cardinal points are the minimum or base, optimum, and maximum or ceiling temperatures. They differ among the different kinds of seed.

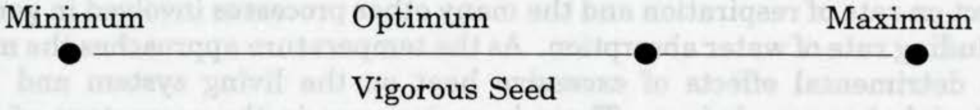
The minimum or base temperature is the temperature below which the processes of germination do not proceed to the point of visible growth of the embryonic axis within a "reasonable" period of time. For many seed kinds the minimum temperature is difficult to establish because of its dependence on time. Since the main effect of a lower temperature on germination is - up to a point - a slowing down of the germination process, the minimum temperature established in a 10 day germination period is usually higher than when a 15 or 20 day period is allowed. Temperatures below the minimum but above freezing are usually not lethal to imbibed seed and do not cause death unless exposure is very prolonged, there is an interaction with seed rotting micro-organisms, or the seed are susceptible to imbibitional chilling injury. The seed generally germinate rather rapidly when the temperature is raised from the sub-minimal level to near the optimum.

The maximum or ceiling temperature is the temperature above which the germination mechanisms fail and visible growth does not occur. In contrast to the minimum temperature, the maximum temperature is rather specific and relatively easy to establish. Further, a temperature above the maximum is usually lethal. Imbibed seed exposed to temperatures above the maximum die and rot within a few days.

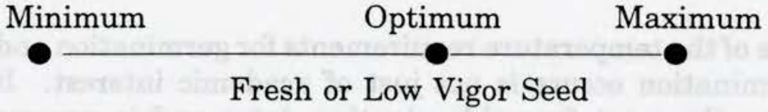
The optimum temperature for germination is the temperature at which the maximum percentage of seed germinate in the shortest period.

The cardinal temperatures for germination and their interrelationships can be illustrated by using a line to represent the temperature range within which germination takes place:

A.



B.



The optimum temperature for germination is generally closer to the maximum than to the minimum. The major effect of reducing temperature from the optimum to the minimum is on the rate of germination. The germination process and early seedling growth become progressively slower as temperature decreases from the optimum. If enough time is allowed, the percentage of germination is about the same. On the other hand, increasing the temperature above the optimum decreases both the rate and percentage of germination regardless of the time period allowed.

The effect of temperature on germination is strongly influenced by the physiological condition of the seed. Newly harvested seed, which are often residually dormant, are usually rather specific in their requirements for germination. This is related to the dormancy condition. Newly harvested rice seed, for example, germinate best at about 32°C, while newly harvested wheat seed do best at 16-18°C. As seed lose their residual dormancy, the optimum temperature shifts to a slightly warmer level and the temperature range for germination increases. The seed become less specific in their requirements for germination. (See diagrams A and B above).

There is another shift in the temperature requirement as seeds deteriorate. The seed again becomes more sensitive to temperature, the temperature range for germination shortens, and the optimum temperature shifts to a cooler level.

Much of the research on temperature relations of germination has been done using constant temperatures. In nature, of course, seed seldom germinate under constant temperatures. In most climatic areas there is a daily fluctuation of temperature from "higher" during the day to "lower" at night. It is not surprising, therefore, that many species germinate better under alternating temperatures than at a constant temperature. Most kinds of forage grass seed, for example, germinate best under such daily alternations of temperature as 15 to 25°C, 20 to 30°C, and 20 to 35°C.

Temperature affects the gemination process in several ways. In general, the rate of germination increases as temperature increases from the minimum to the optimum and even slightly above the optimum. Temperature has a pronounced effect on rate of respiration and the many other processes involved in germination including rate of water absorption. As the temperature approaches the maximum, the detrimental effects of excessive heat on the living system and biological materials become obvious. There is an increase in the percentage of abnormal seedlings and decayed seed. When the temperature exceeds the maximum, all of the seed die within a few days.

Knowledge of the temperature requirements for germination and the range within which germination occurs is not just of academic interest. It is important in establishing the most favorable planting dates and in unraveling many stand establishment problems.

Mobilization of Energy and Food Reserves

The absorption of water by seed "turns on" and/or accelerates metabolic processes which lead to the resumption of active growth of the embryonic axis in the seed and support early seedling development. One of the basic processes accelerated is respiration.

Energy is required for the resumption of active growth of the embryonic axis - for germination and many of the processes that support germination. The energy required is provided by respiration. An air dry seed at 10-13% moisture content respires but at a very low rate. During the water absorption phase of the germination process, the rate of respiration increases dramatically. Some of the energy released during respiration is in the form of heat, but most is converted from some chemical forms to others.

The process of respiration requires a readily available substrata - an organic compound which can be oxidized to release energy. The basic respiratory substrate is a simple sugar called glucose. During respiration glucose is oxidized by complicated processes to carbon dioxide and water with the release of a substantial quantity of energy. In green plants the organic compounds required for respiration are formed by the process of photosynthesis, thus the sun is the ultimate source of energy for plant growth and the production of seed and the other plant materials that man harvests.

Since photosynthesis is not re-established until after germination is complete and the seedling has developed to a certain extent, the germination process is dependent on reserve organic compounds stored in the seed for energy and other materials. Some of those organic compounds are in the embryonic axis in readily usable forms, e.g., sucrose, and serve as respiratory substrata for the early phase of the germination process. The bulk of the reserve materials, however, are in the form of complex, non-mobile (non-translocatable) forms located in specialized tissue within the seed. These compounds must be broken down to simple, translocatable forms to make them available for germination.

The reserve materials in seed occur in three major forms: starch and other complex carbohydrates, fats and oils, and proteins. The processes which transform these materials into usable, translocatable forms are termed "mobilization of reserves." (See Figure 3).

Starch is the principal reserve in cereals and other species of the grass family. It is stored in the endosperm. During the early phase of gemination, gibberellin, a hormone present in the scutellum (part of the embryo or gem), moves into the outermost layer of the endosperm and stimulates the activity of hydrolytic enzymes which catalyze the breakdown of starch into glucose. One of the steps involved in the breakdown of starch is the production of maltose, which is, of course, important in the brewing industry. Glucose is a simple sugar and easily translocated. It moves from the endosperm into the scutellum where it is converted into sucrose. Sucrose is then translocated to the active sites in the embryonic axis for use. The mobilization of stored starch and other complex carbohydrates in non-grass species such as peas is somewhat different but the end result is the same - respiratory substrata is made available to the active sites of the embryonic axis.

When all plant species are considered, the most frequent reserve material is fats and oils. The evolutionary significance of this situation is that fats and oils - or lipids - have a higher energy value than starch or proteins. Fats and oils are broken down by enzymic activity to fatty acids and glycerol. Glycerol is further broken down to simple compounds which can enter into the respiratory process, or it can be incorporated in "new" fats and oils. Likewise, the fatty acids are further degraded into fragments that are readily usable in the respiratory process or for re-conversion into other materials.

The proteins stored in seed are broken down by enzymic activity into amino acids. The amino acids liberated are translocatable and are used for synthesis of the new proteins required for other enzymes, and new plant material, i.e., for growth. Or, they can be oxidized to provide energy.

The reserve materials stored in seed provide the energy and "building blocks" needed for resumption of active growth of the embryonic axis and growth and development of the young seedlings. These materials are made available to the embryonic axis by "mobilization" processes. As the seedling develops, photosynthesis is re-established and it becomes independent of the reserves stored in the endosperm or cotyledons which decay or shrivel and drop from the seedling.

Man cultivates many species of plants for the reserve materials stored in seed for his own consumption or for animal feed. Wheat and other cereals are milled to produce flour for bread and pastries or for brewing. Rice is consumed directly.

STARCH

$$\text{Starch} \xrightarrow{\text{amylases}} \text{Maltose + Glucose}$$

$$\text{Maltose} \xrightarrow{\text{maltase}} \text{Glucose}$$

PROTEINS

$$\text{Proteins} \xrightarrow{\text{proteinases}} \text{Amino Acids}$$

FATS AND OILS
(Lipids)

$$\text{Lipids} \xrightarrow{\text{lipases}} \text{Glycerol + Fatty Acids}$$

$$\text{Glycerol} \xrightarrow{\qquad} \text{Respiratory Substrata}$$

$$\text{Fatty Acids} \xrightarrow{\qquad} \text{Acetyl-CoA}$$

Figure 3. Mobilization of food reserves in seed during germination.

Corn and sorghum are used as human and animal feeds, or for other products such as edible oil. All of these kinds of seed store primarily starch. The legumes such as beans, soybeans, peanuts, etc., and species from other families are consumed directly or milled to produce vegetable oils and protein residues. Man is fortunate indeed that the seed habit in higher plants evolved with an abundance of reserves to support the process of germination.

Resumption of Active Growth

The acceleration of respiration during imbibition and the mobilization of organic reserves provide the energy, fuel and building materials needed for gemination - the resumption of active growth of the embryonic axis. Growth involves cell elongation and expansion and cell division, i.e., the production of new cells.

Although the data and observations are not entirely in agreement, it appears that the first manifestations of resumed growth are the result of the elongation or expansion of existing cells. And, for most kinds of seed, cell elongation and expansion begins in the "embryonic" radicle or root. Cell division is initiated later - a few hours or even days after the onset of cell elongation.

In some species, cell elongation is sufficient to cause the radicle to emerge through the seed coat. Both cell elongation and division are involved in emergence of the radicle in other species. The time of radicle emergence is variable among seed kinds and greatly influenced by temperature. At a constant temperature of 30°C (86°F) radicle emergence in corn, soybean, sorghum and cotton seed can occur between 30-38 hrs.

The resumption of active growth begins in the radicle part of the embryonic axis then "spreads" to the plumule or epicotyl which will develop into the stem, leaves, branches, etc., of the plant.

During the germination process, some organic materials are "consumed", while others are synthesized. Since there is no input of new materials into a germinated seed, an overall decrease in dry weight occurs along with a redistribution of dry weight. Dry weight is "transferred" from the storage tissue (cotyledons, endosperm) to the growing embryonic axis, i.e., the seedling. The rate and degree of this transfer of "dry weight" from storage tissue to the seedling has been shown to be related to vigor in some kinds of seed.

In the soil the developing radicle or root responds positively to gravity and grows downward. The plumule or epicotyl responds negatively to gravity and begins to grow upward. Most seedlings can be classified into two groups on the basis of the "movement" of the storage tissue (or cotyledons). The storage tissue (endosperm) and one-cotyledon of seed of members of the grass family - corn, wheat, sorghum, etc. - remain in place in the soil, and the plumule emerges. Emergence of the plumule is facilitated by a conical sheath - the coleoptile - which encloses the leaves and growing point. The germination mode that maintains the storage tissue and cotyledons in place in the soil is called hypogeal germination. True peas have a hypogeal mode of germination - the cotyledons remain in the soil while the epicotyl or short emerges. (Figure 4).

The germination mode in cotton, beans, soybeans, sunflower, and peanuts is epigeal. The cotyledons or storage tissue are raised out of the soil. This is accomplished by growth of the hypocotyl - the portion of the seedling between the cotyledons and radicle. In soybeans, the hypocotyl emerges above ground in a sort of "doubled" position. It then straightens and pulls the cotyledons out of the soil. The seed coat is usually shucked during this process.

During emergence and seedling establishment, reserves are continually drawn from the storage tissue. Cotyledons that emerge above the soil generally become green and photosynthetic. Later, they shrivel and are dropped from the developing plant. Storage tissue and cotyledons that remain below the soil do not, of course, become green and photosynthetic. They serve in a nutritive role until the reserves are exhausted and then decay.

As the seedlings develops, a photosynthetic capability is established and it becomes autotropic - i.e., independent of stored food reserves for its nutrition. And, the growth and development cycle of the plant continues.

The term germination is properly associated with the resumption of active growth of the embryonic axis in a seed. However, it is also applied to the resumption of active growth of the buds and other meristemic areas in vegetative structures used for propagation of plants. A potato is not a seed but has many similarities in structure and function. A potato tuber has a covering, stored food, and a bud. When exposed to favorable conditions, the stored food is mobilized, and the bud resumes active growth - the potato germinates and a "seedling" develops. A joint of sugar cane, a tulip bulb, an iris rhizome also function in many ways like a seed.

Germination is a basic process in plants. Only in recent years have we begun to understand its complexity and some of the intricate mechanisms involved. As our knowledge grows and the mechanisms involved become clearer, greater control of the germination process should be possible for the benefit of crop production.

Considering the complexity of germination and the many mechanisms involved, it is not surprising that the process can and does fail. Nature compensates for germination failures by a general abundance in seed production. Man has followed this same route in crop production. Traditionally, a relative abundance of seed is planted to compensate for gemination failures. Although this tradition is still followed, it is becoming increasingly inappropriate in modern crop production.

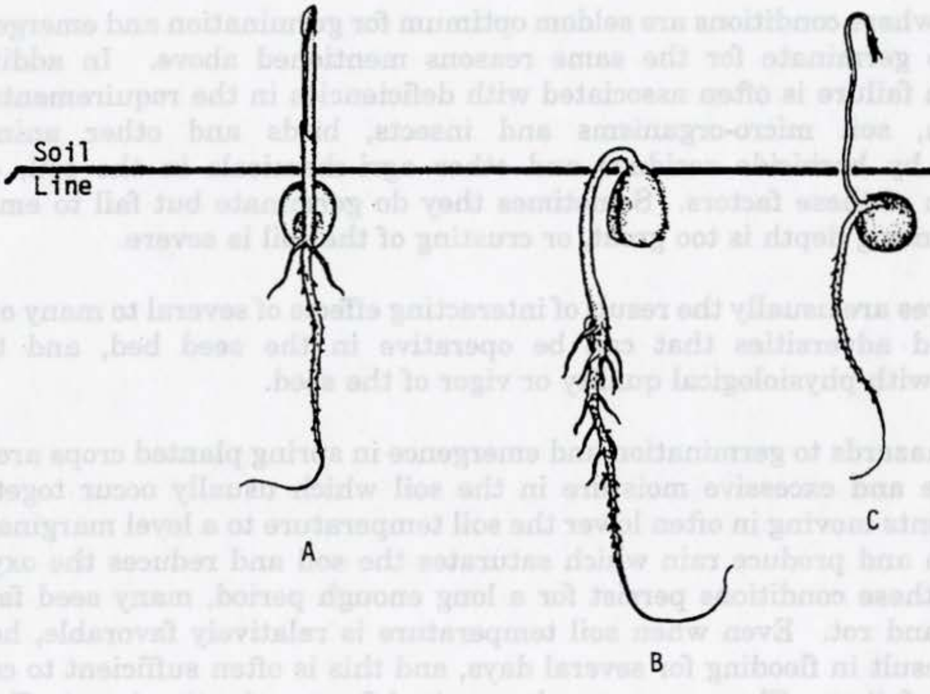


Figure 4. Emerging seedlings of: sorghum, A; soybeans, B; and peas, C.

Germination Failure

Seed fail to germinate and develop into seedlings for many reasons. Under the optimum conditions in the laboratory, germination failure is usually associated with dormancy, severe mechanical damage, or deterioration that has progressed to the point of loss of the capacity to germinate.

In the field where conditions are seldom optimum for germination and emergence, seed fail to germinate for the same reasons mentioned above. In addition, germination failure is often associated with deficiencies in the requirements for germination, soil micro-organisms and insects, birds and other animals, toxification by herbicide residues and other agri-chemicals in the soil, or a combination of these factors. Sometimes they do germinate but fail to emerge because planting depth is too great, or crusting of the soil is severe.

Stand failures are usually the result of interacting effects of several to many of the hazards and adversities that can be operative in the seed bed, and their interaction with physiological quality or vigor of the seed.

The major hazards to germination and emergence in spring planted crops are low temperature and excessive moisture in the soil which usually occur together. Weather fronts moving in often lower the soil temperature to a level marginal for germination and produce rain which saturates the soil and reduces the oxygen supply. If these conditions persist for a long enough period, many seed fail to germinate and rot. Even when soil temperature is relatively favorable, heavy rains can result in flooding for several days, and this is often sufficient to cause germination failure. The oxygen supply required for germination is cut off.

Preparation of the seed bed often dries the soil to a level marginal for germination, especially in the top two inches. Under such conditions some farmers plant deep to get the seed "into the moisture", while other plant shallow and hope for a rain. A heavy rain on deep planted seed can produce a thick compact zone and crust which defies emergence of many kinds of seed. A shallow planting depth would produce better results. However, shallow planting in anticipation of rain can also be disastrous when the rain doesn't come. The seed absorb some moisture and increase in moisture content, but not enough for germination. Sunny weather warms the top few inches of soil. The combination of elevated seed moisture content and warm temperatures causes rapid deterioration so that the seed weaken and die if rain is delayed long enough.

Although cold or cool soil temperatures are usually the most adverse for spring planted, warm season crops, high soil temperatures can also be detrimental. Germination failure of soybean seed begins at a temperature of about 100°F even when other conditions are good. Soil temperatures in the South - toward the end of the soybean planting period in late June and early July - can rise well above

100°F during the day, and not drop lower than 90°F during the night. Treated seed usually survive such conditions - until the temperature moderates - better than untreated seed.

Treatment of seed with fungicides also indirectly protects them against other adversities such as low temperature, excessive moisture and so on. The fungicides don't cause the seed to germinate at lower temperatures or reduced oxygen. Rather, they protect the seed from soil micro-organisms which attack and destroy seed when conditions are not favorable for rapid germination and emergence.

The interaction of seed vigor and stresses in the seed bed in stand failures is well established. Vigorous seed are less sensitive to conditions in the seed bed than seed low in vigor. Therefore, they germinate and emerge under a wider range of temperatures, soil moisture levels, and are most resistant to attack by soil micro-organisms. When conditions are extremely adverse, however, even high vigor seed fail to germinate and/or emerge.

Over-planting is the traditional response to the unpredictability of field conditions, hence, uncertainty regarding emergence. Many more seed are planted than required to produce a desirable plant population when conditions are favorable: "one for the crow, one for the snow, and one to grow". When the crows don't come around and the snow falls elsewhere, the excessive plants need to be thinned. Cotton seed, for example, used to be drilled thickly to ensure an adequate stand. When conditions favored a more than adequate stand, a lot of "cotton chopping" had to be done.

The modern trend in crop production is planting to a stand. A certain number of seed are planted per acre at specific in-row and between-row spacings with the expectation that a certain number of plants will be produced. The requirements for planting to a stand are high quality seed, and close monitoring of weather conditions so that planting is done when the probability of favorable conditions for germination and emergence is high. Presently, planting to a stand is standard practice in corn production and the production of many kinds of vegetables. Yield and quality of yield in these crops is closely associated with plant population and/or spacing and thinning is prohibitively expensive. There is no doubt that the practice of planting to a stand will be extended to other crops. When it is, germination failure will become even more important than it is now.

Summary

Germination is the crucial and final event in the life of a seed. It can be defined as the resumption of active growth of the embryonic axis. A seed requires moisture, a favorable temperature and oxygen for germination. Rehydration of the seed sets in motion a chain of reactions which provide the energy and building blocks for the resumption of active growth and development of the young seedling.

Germination failure is caused by many factors and conditions. These range from deterioration of the seed and loss of the geminative capacity to the mechanical impedance to emergence from soil crusts formed after sowing.