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The Concept and Process of Seed Germination – A Review

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Abstract

For germination to occur, the environmental conditions must be favorable in order to support the growing plant. The soil depth, amount of water, and temperature are all critical conditions that must be met in order for the process of germination to be initiated. Typically, the soil conditions must be moist and warm. When environmental conditions are optimal, germination is initiated by a process termed water imbibition. The seed absorbs water through a structure called a micropyle, which induces swelling of the seed until it splits open. Once the seed has ruptured, the radicle (primary root) and plumule (shoot) can emerge from the seed. This process is initiated by specific enzymes that become activated when the seed is exposed to water. The roots grow downwards, and the shoot grows upwards towards the soil surface. Once the shoot emerges from the soil surface, the cotyledons become fully unfolded and expand, eventually forming the first leaves. Once this occurs, the plant is ready to initiate photosynthesis and is considered a seedling.

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Seed germination, Soil condition, Enzymes, Cotyledons

Introduction

The term germination in the seeds of higher plants (Angiosperms) refers to the protrusion of a root or shoot from the seed coat, while emergence is the visible penetration of the shoot above the soil surface (Hadas and Russo 1974, Hadas 1976, Benech Arnold *et al.*, 1991). In order that a seed can germinate, it must be placed in environmental conditions favorable to this process (Craufurd *et al.*, 1996). Among the conditions required is an adequate supply of water, a suitable temperature range and, for some seeds, light (Collis George and Williams 1968, Levitt 1980, Long and Woodward 1998). 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 (James and Delouche, 1979).

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. In the germination process, the seed's role is that of a reproductive unit; it is the thread of life that assures survival of all plant species. Furthermore, because of its role in stand establishment, seed germination remains a key to modern agriculture. Thus, especially in a world acutely aware of the delicate balance between food production and world population, a fundamental understanding of germination is essential to crop production.

Every species has some mechanism for delaying germination until after the seed has been dispersed. The Science of Seed Germination is the discovery and description of such mechanisms and the development of procedures for removing them so that the seeds can germinate (Norman C. Deno, 1993). Therefore, the objective of this review paper is to review the concept and process of seed germination and to review the requirements, failure and type of seed germination

Concepts of seed germination

Various definitions of seed germination have been proposed, and it is important to understand their distinctions. The seed physiologist, germination is defined as the emergence of the radicle through the seed coat. Such a definition says nothing about other essential structures such as the epicotyl or hypocotyls that become the above ground parts of a successful seedling. To the seed analyst, germination is "the emergence and development from the seed embryo of those essential structures which, for the kind of seed in question, are indicative of the ability to produce a normal plant under favorable conditions." This definition focuses on the reproductive ability of the seed, an essential objective in agriculture.

Does it have the capacity to produce a normal plant? Others consider germination to be the resumption of active growth by the embryo resulting in the rupture of the seed coat and emergence of a young plant. This definition presumes that the seed has been in a state of quiescence, or rest, after its formation and development. During this period of rest, the seed is in a relatively inactive state and has a low rate of metabolism. It can remain in that state until environmental conditions trigger the resumption of active growth. Regardless of which definition is preferred, it should be emphasized that one cannot actually seed the process of germination unfold. Germination is generally associated with emergence of the radicle through the seed coat. The International Seed Testing Association (ISTA 2004) defines germination as "the emergence and development of the seedling to a stage where the aspect of its essential structures indicates whether it is able to develop further into a satisfactory plant under favorable conditions". Therefore, all definitions include some measure of seedling development, even though this occurs subsequent to the germination event (ISTA 2004).

Germination is a process by which the embryo in the seed becomes activated and begins to grow into a new seedling. Germination is usually the growth of a plant contained within a seed; it results in the formation of the seedling; it is also the process of reactivation of metabolic machinery of the seed resulting in the emergence of radicle and plumule.

Germination as part of plant's life history strategy, it is an irreversible biological process: Once germination has started the embryo is committed irrevocably to growth or death (Baskin and Baskin, 2014). Generally, inorder for the seeds of a species to germinate, they must be in suitable environmental conditions "germination niche" which usually favour the growth and establishment of the seedlings (Harper, 1977).

Roles of seeds on germination

The seed of a vascular plant is a small package produced in a fruit or cone after the union of male and female reproductive cells. All fully developed seeds contain an embryo and, in most plant species some store of food reserves, wrapped in a seed coat. Some plants produce varying numbers of seeds that lack embryos; these are empty seeds which never germinate. Dormant seeds are ripe seeds that do not germinate because they are subject to external environmental conditions that prevent the initiation of metabolic processes and cell growth. Under proper conditions, the seed begins to germinate and the embryonic tissues resume growth, developing towards a seedling. In the life cycle of a plant species germination processes are a more crucial phase which greatly affecting its population dynamic, regeneration and fitness as well as its persistence (Fenner and Thompson, 2005).

A seed is a mature ovule, which is formed after the fertilization. The outer covering of a seed is called seed-coat which is a protective covering and is known as

Testa. Seeds contain a small opening called micropyle through which water enters into the seed. The inner layer below the testa is called tegmen. Inside, seeds contain embryo which consists of cotyledons, radicle and plumule. Seed contains endosperm. However, the endosperm is absent in some seeds. Hilum is a scar, where the seed breaks from the stalk of the ovule wall (Fenner and Thompson, 2005).

Types of seeds according to the number of cotyledons

Seeds are of two types according to the number of cotyledons.

A. Monocotyledonous Seeds:

These seeds contain only one cotyledon; for example, wheat, bajra, maize and rice. (Fig. 3.1)

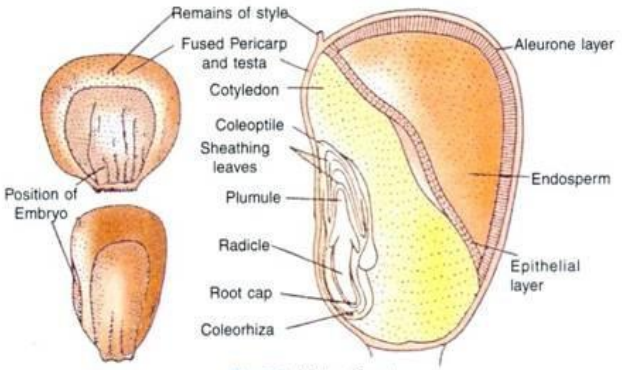


Fig. 3.1. Maize Seed.

B. Dicotyledonous Seeds:

These seeds contain two cotyledons; for example, mango, gram and pea. (Fig. 3.2)

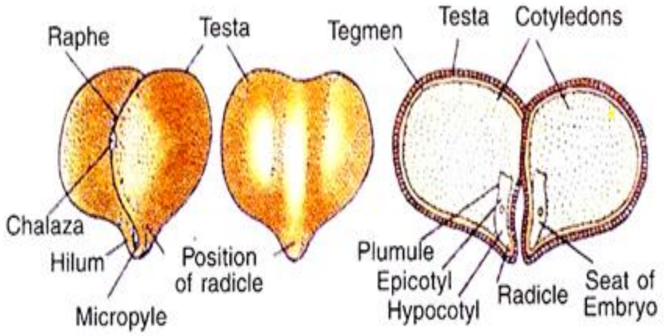


Fig. 3.2. Gram seed.

Types of seeds according to the food storage tissue

There are two types of seeds according to the food storage tissue.

A. Endospermic Seeds (Albuminous):
Endospermic seeds are those in which food is stored in endosperm, e.g., wheat, rice and bajra.

B. Non-Endospermic Seeds (Exalbuminous):
Non-endospermic seeds are those in which food is stored in cotyledons, e.g., pea and gram.

Requirements for germination

Water

Water is required for germination. Mature seeds are often extremely dry and need to take in significant amounts of water, relative to the dry weight of the seed, before Cellular metabolism and growth can resume. Most seeds need enough water to moisten the seeds but not enough to soak them. The uptake of water by seeds is called imbibition, which leads to the swelling and the breaking of the seed coat. When seeds are formed, most plants store a food reserve with the seed, such as starch, proteins, or oils. This food reserve provides nourishment to the growing embryo. When the seed imbibes water, hydrolytic enzymes are activated which break down these stored food resources into metabolically useful chemicals . After the seedling emerges from the seed coat and starts growing roots and leaves, the seedling's food reserves are typically exhausted; at this point photosynthesis provides the energy needed for continued growth and the seedling now requires a continuous supply of water, nutrients, and light (*Eichhorn et al., 2005).*

Oxygen

Oxygen is necessary for respiration which releases the energy needed for growth. Germinating seeds respire very actively and need sufficient oxygen. The germinating seeds obtain this oxygen from the air contained in the soil. It is for this reason that most seeds sown deeper in the soil or in water-logged soils (i.e. oxygen deficient) often fail to germinate due to insufficient oxygen. Ploughing and hoeing aerate the soil and facilitate good germination is required by the germinating seed for metabolism (Siegel and Rosen 1962).

Oxygen is used in aerobic respiration, the main source of the seedling's energy until it grows leaves. Oxygen is an atmospheric gas that is found in soil pore spaces; if a seed is buried too deeply within the soil or the soil is waterlogged, the seed can be oxygen starved. Some seeds have impermeable seed coats that prevent oxygen from entering the seed, causing a type of physical dormancy which is broken when the seed coat is worn away enough to allow gas exchange and water uptake from the environment (*Eichhorn et al., 2005).*

Temperature

Temperature affects cellular metabolic and growth rates. Seeds from different species and even seeds from the same plant germinate over a wide range of temperatures. Seeds often have a temperature range within which they will germinate, and they will not do so above or below this range. Many seeds germinate at temperatures slightly above 60-75 F (16-24 C) [room-temperature in centrally heated houses], while others germinate just above freezing and others germinate only in response to alternations in temperature between warm and cool. Some seeds germinate when the soil is cool 28-40 F (-2 - 4 C), and some when the soil is warm 76-90 F (24-32 C). Some seeds require exposure to cold temperatures (vernalization) to break dormancy. Some seeds in a dormant state will not germinate even if conditions are favorable. Seeds that are dependent on temperature to end dormancy have a type of physiological dormancy. For example, seeds requiring the cold of winter are inhibited from germinating until they take in water in the fall and experience cooler temperatures. Cold stratification is a process that induces the dormancy breaking prior to light emission that promotes germination (Baskin and Baskin, 2014).

Four degrees Celsius is cool enough to end dormancy for most cool dormant seeds, but some groups, especially within the family Ranunculaceae and others, need conditions cooler than -5 C. Some seeds will only germinate after hot temperatures during a forest fire which cracks their seed coats; this is a type of physical dormancy.

Most common annual vegetables have optimal germination temperatures between 75-90 F (24-32C), though many species (e.g. radishes or spinach) can germinate at significantly lower temperatures, as low as 40 F (4 C), thus allowing them to be grown from seeds in cooler climates. Suboptimal temperatures lead to lower success rates and longer germination periods(Baskin CC, and Baskin JM,2014).

Light or darkness

Can be an environmental trigger for germination and is a type of physiological dormancy. Most seeds are not affected by light or darkness, but many seeds, including species found in forest settings, will not germinate until an opening in the canopy allows sufficient light for growth of the seedling, Scarification mimics natural processes that weaken the seed coat before germination. In nature, some seeds require particular conditions to germinate, such as the heat of a fire (e.g., many Australian native plants), or soaking in a body of water for a long period of time. Others need to be passed through an animal's digestive tract to weaken the seed coat enough to allow the seedling to emerge, (*Eichhorn S. etal.2005).*

The process of seed germination

Germination com- mences with the uptake of water by the dry seed-imbibi- tion-and is completed when a part of the embryo, usually the radicle, extends to penetrate the structures that sur- round it.The process of seed germination includes the following five changes or steps.Such five changes or steps occurring during seed germination are: (1) Imbibition (2) Respiration (3) Effect of Light on Seed Germination(4) Mobilization of Reserves during Seed Germination and Role of Growth Regulators and (5) Development of Embryo Axis into Seedling.

Imbibition and the resumption of metabolism

Uptake of water by a mature dry seed is triphasic (Figure I), with a rapid initial uptake (phase I) followed by a plateau phase (phase 11). A further increase in water uptake occurs only after germination is completed, as the embryonic axes elongate. Because dormant seeds do not complete germi- nation, they cannot enter phase 111. The influx of water into the cells of dry seeds during phase I results in temporary structural perturbations, particularly to membranes, which lead to an immediate and rapid leakage of solutes and low molecular weight metabolites into the surrounding imbibition solution. This is symptomatic of a transition of the membrane phospholipid components from the gel phase achieved during maturation drying to the normal, hydrated liquid-crystalline state (Crowe and Crowe, 1992).

Within a short time of rehydration, the membranes re- turn to their more stable configuration, at which time solute leakage is curtailed. How repair to desiccation-and rehydration-induced dam- age to membranes and organelles is achieved is unknown. However, during the imbibition of cotton seeds, the amount of N-acetyl phosphatidylethanolamine, a phospholipid with membrane-stabilizing properties, increases, as does that of the corresponding synthase. These molecules may be in- volved in maintaining or enhancing membrane integrity (Sandoval *et al.*, 1995). Upon imbibition, the quiescent dry seed rapidly resumes metabolic activity. The structures and enzymes necessary for this initial resumption of metabolic activity are generally assumed to be present within the dry seed, having survived, at least partially intact, the desiccation phase that terminates seed maturation. Reintroduction of water during imbibition is sufficient for metabolic activities to resume, with turnover or replacement of components occurring over severa1 hours as full metabolic status is achieved (Figure 1). One of the first changes upon imbibition is the resumption of respiratory activity, which can be detected within min- uses. After a steep initial increase in oxygen consumption, the rate declines until the radicle penetrates the surrounding structures. At this time, another burst of respiratory activity occurs (Botha *et al.*, 1992; Bewley and Black, 1994). The glycolytic and oxidative pentose phosphate pathways both resume during phase I, and the Kreb's cycle enzymes become activated (Nicolas and Aldasoro, 1979; Salon *et al.*, 1988). Germinating seeds of many species frequently produce ethanol (Morohashi and Shimokoriyama, 1972). This is often the result of an internal deficiency in oxygen that is caused by restrictions to gaseous diffusion by the structures that surround the seed and by the dense internal structure of most seeds. This oxygen deficiency may result in more pyruvate production than utilization for activities of the Kreb's cycle and electron transport chain. Tissues of the mature dry seed contain mitochondria, and although these organelles are poorly differentiated as a consequence of maturation drying, they contain sufficient Kreb's cycle enzymes and terminal oxidases to provide adequate amounts of ATP to support metabolism for several hours after imbibition (Ehrenshaft and Brambl, 1990; Attucci *et al.*, 1991). During germination of embryos, there appear to be two distinct patterns of mitochondrial development. These patterns, which are particularly obvious in cotyledons, depend on the nature of the stored reserves. In starch-storing seeds, repair and activation of preexisting organelles predominate, whereas oil-storing seeds typically produce new mitochondria (Morohashi and Bewley, 1980; Morohashi, 1986). For example, the biogenesis of mitochondria in germinating maize embryos (which store oil in the scutellum, although starch is the major endosperm reserve) involves the synthesis of cytochrome c oxidase subunits encoded by the organellar genome, which is followed within hours by the synthesis of nuclear-encoded subunits (Ehrenshaft and Brambl, 1990). This observation also implies that the coordinated regulation of mitochondrial and nuclear genomes in plants begins during the early stages of germination

Protein synthesis during germination

All of the components necessary for the resumption of protein synthesis upon imbibition are present within the cells of mature dry embryos, although polysomes are absent. However, within minutes of rehydration there is a decline in the number of single ribosomes as they become recruited into polysomal protein-synthesizing complexes. Initial protein synthesis is dependent on extant ribosomes, but newly synthesized ribosomes are produced and used within hours of initial polysome assembly (Dommes and Van der Walle, 1990). Preformed mRNAs are also present within the dry embryo. Some of these are residual messages associated with previous developmental processes (Comai and Harada, 1990; Lane, 1991) and may be used transiently during early germination (Figure 1). Messages encoding proteins that are important during seed maturation and drying, such as late embryogenesis abundant (LEA) proteins, are likely to be de- graded rapidly upon imbibition (Jiang and Kermode, 1994; Han *et al.*, 1996). Conversely, those encoding proteins re- quired during early germination (e.g., ribosomal protein messages; Beltrán-Peíia *et al.*, 1995) are replaced by identi- cal messages at later times, with protein synthesis becoming more dependent on the new transcripts with time (Figure 1; Bewley, 1982). The nature of the stored messages in seeds has not been studied extensively, although it is known that they are likely to be present in association with proteins as mRNP complexes (Ajtkhozhin *et al.*, 1976; Peumans *et al.*, 1979). An alternative possibility is that stored tran- scripts remain sequestered within the nucleus (Hammett and Katterman, 1975). New mRNAs are transcribed as germination proceeds. The majority of these are likely to encode proteins essential for the support of normal cellular metabolism, that is, “growth maintenance” reactions that are not restricted to germination (Bewley and Marcus, 1990). Indeed, no specific protein markers exclusive to germination have been found. Therefore, it is cautioned here that many so-called germination-specific mRNAs reported in the literature encode enzymes integral to the mobilization and conversion of the major stored reserves;

these are postgerminative events that are important during seedling growth, but they are unrelated to germination per se (Figure 1). Nevertheless, some changes in embryo mRNA populations and synthesized proteins do occur during germination of severa1 species of monocots (e.g., maize; Sánchez-Martinez *et al.*, 1986), di- cots (e.g., peas; Lalonde and Bewley, 1986), and conifers (e.g., loblolly pine; Mullen *et al.*, 1996). The importance of these newly synthesized proteins to the completion of germination of the embryo remains to be elucidated. One promising candidate for a "germination-specific" gene could be the one that encodes the protein germin (Lane, 1991), which is an oxalate oxidase. However, by its nature, the timing of its synthesis, and its potential meta- bolic functions (Lane, 1994), germin is more likely to be involved with postgerminative cell elongation. Thus, the search for specific protein markers with an exclusive role in germination must continue.

Radicle extension and the completion of germination

With few exceptions, radicle extension through the structures surrounding the embryo is the event that terminates germination and marks the commencement of seedling growth. This extension may or may not be accompanied by cell division. Two discrete phases of DNA synthesis occur in the radicle cells after imbibition (Figure 1). The first takes place soon after imbibition and probably involves the repair of DNA damaged during maturation drying and rehydration as well as the synthesis of mitochondrial DNA. DNA synthesis associated with postgerminative cell division ac- counts for the second phase (Figure 1;Zlatnova *et al.*, 1987; Osborne and Boubriak, 1994). Extension of the radicle is a turgor-driven process that re- quires yielding of walls in those cells of the embryonic root axis that lie between the root cap and the base of the hypo- cotyl (see Cosgrove, 1997, in this issue, for a review of cell expansion). There are three possible reasons for the commencement of radicle growth. One possibility is that late during germination, the osmotic potential ((JIT) of the radicle cells becomes more negative because of the accumulation of solutes, perhaps as a result of the hydrolysis of polymeric reserves present within the radicle cells themselves. The decrease in $7~ would lead to increased water uptake, and the resulting increase in turgor would drive cell extension. However, there is no consistent evidence for changes in cellular (JIT during germination (Welbaum and Bradford, 1990; Bradford, 1995). A second possibility is that extensibility of the radicle cell walls allows for their elongation. Whether the mechanisms by which cells of the radicle become more extensible differs from those in other tissues is not known. Cell wall loosening may result from the cleavage and rejoining of xyloglucan molecules that tether adjacent cellulose microfibrils, which would permit expansion by microfibril separation. The activ- ity of xyloglucanendotransglycosylase (XET), an enzyme capable of reversibly cleaving xyloglucan molecules, in- creases in the apical region of maize seedling roots during their elongation (Wu *et al.*, 1994), but this increase occurs after germination is completed. Alternative candidates for cell wall-loosening proteins are the expansins, which have the ability to disrupt the hydrogen bonds between cell wall polymers (e.g., matrix polysaccharides and cellulose microfibrils). Expansins have been strongly implicated in the expansion of cucumber hypocotyls (McQueen-Mason and Cosgrove, 1995; see Cosgrove, 1997, in this issue). How- ever, neither of these cell wall-loosening proteins has been reported in germinating seeds. Moreover, both XET and expansin activities in seedlings appear to be enhanced by auxin, which is generally regarded as ineffective in promoting seed germination, and XET activity in maize seedling roots is also enhanced by abscisic acid (ABA), a potent in- hibitor of embryo radicle elongation! A third possibility is that the seed tissues surrounding the radicle tip weaken, thus allowing the tip to elongate. Be- cause there are no changes in cell +TI before radicle growth commences, it is axiomatic that the turgor potential (+p) of the radicle cells is sufficient to drive their elongation if there is little or no restraint exerted by the surrounding structures. In many germinating seeds, including those of rape, the testa splits during imbibition, and it is only the rigidity of the radicle cell walls that restrains growth (Schopfer and Plachy, 1985). As the walls yield during the initial stages of radicle elongation, there is a decline in cell Jlp. Conversely, in other seeds, Jlp alone is insufficient to drive wall extension, and there is a severe constraint on radicle cell growth imposed by the surrounding structures. In lettuce, tobacco, and tomato seeds, the endosperm is the constraining structure, whereas in muskmelon it is the perisperm. A reduction in the resistance of these enclosing structures is necessary for germination to be completed. Measurements have revealed a decline in the mechanical resistance of the structures covering the embryo root cap at the time of radicle emergence in the endosperm of pepper seeds (Watkins and Cantliffe, 1983) and the perisperm of muskmelon seeds (Welbaum *et al.*, 1995). This decline in resistance is likely to be achieved by cell wall hydrolases, such as hemicellulases, produced within and secreted by the endosperm itself, a subject that is considered in the next section.

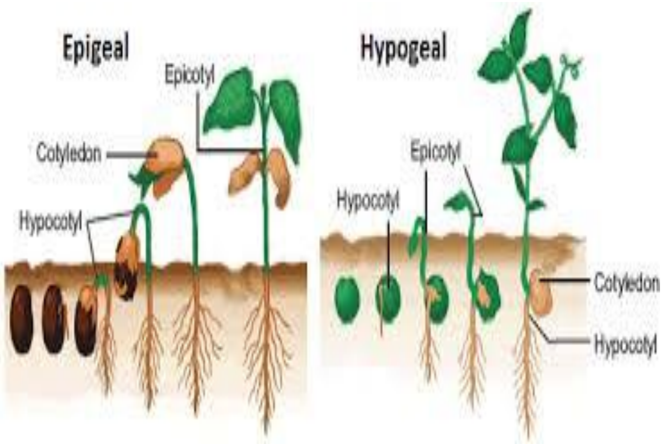
Types of seed germination

Hypogeal germination

Hypogeal germination implies that the cotyledons stay below the ground. The epicotyl (part of the stem above the cotyledon) grows, while the hypocotyl (part of the stem below the cotyledon) remains the same in length. In this way, the epicotyl pushes the plumule above the ground. In this kind of germination, the cotyledons do not come out of the soil surface. In such seeds the epicotyl (i.e., part of embryonic axis between plumule and cotyledons) elongates pushing the plumule out of the soil. All monocotyledons show hypogeal germination. Among dicotyledons, gram, pea, groundnut are some common examples of hypogeal germination (Parolin et al., 2003).

Epigeal germination

Epigeal germination implies that the cotyledons are pushed above ground. The hypocotyl elongates while the epicotyl remains the same in length. In this way, the hypocotyl pushes the cotyledon upward. In seeds with epigeal germination, the cotyledons are brought above the soil due to elongation of the hypocotyl. In castor, cotton, papaya, onion, flat green leaf like cotyledons can be seen in the young seedlings. Here the cotyledons, besides food storage, also perform photosynthesis till the seedling becomes independent. In some other plants like bean, the cotyledons being thick, do not become leaf-like; they shrivel and fall off after their food reserves are consumed by the seedling. Examples: Common Beans, Castor, Sunflower, Pumpkin, Watermelon, Cucumber, Gourds, Lilies (Parolin *et al.,* 2003).



Vivipary (Viviparous Germination)

Vivipary is the phenomenon of giving birth to young ones in advanced stage of development. It occurs in mammals (among animals) and mangrove plants. In mangrove plants (e.g., Rhizophora, Sonneratia, Heritiera) the seeds cannot germinate on the ground because of the excessive salt content and lack of oxygen in marshy habitat. In such plants seed dormancy is absent.

Mangrove seeds usually germinate within the fruits which are still attached to the parent plant. This phenomenon is known as vivipary. Examples of viviparous mangroves are Rhizophora, Bruiguiera, Kandelia, and Ceriops etc. The embryo of the seed (present inside the fruit) continues growth while the latter is attached to the parent plant. Hypocotyl elongates and pushes the radicle out of the seed and the fruit. Growth continues till the hypocotyl and radicle become several centimeters long (more than 70 cm in Rhizophora). The seedling becomes heavy. As a result, it breaks its connection with the fruit and falls down in the salt rich muddy water in such a position that the plumule remains outside the saltish water while the tip of the radicle gets fixed in the mud. This protects the plumule. The radicle quickly forms new roots and establishes the seeding as a new plant (Fig. 4.9).

Germination parameters

A large proportion of experiments relating seed germination to time and rate calculations face difficulty in interpreting and analyzing results (Finch-Savage *et al.*, 1998, Trudgill *et al.*, 2000, Grundy *et al.*, 2000). The methods used to evaluate seed germination and emergence are analytical or graphical (Scott *et al.*, 1984), but germination data have several characteristics that distinguish them from other data frequently collected in plant research. Germination is considered to be a qualitative developmental response of an individual seed that occurs at a point in time, but individual seeds within a treatment respond within different times (Harper and Benton 1966, Orchard 1977, Scott *et al.*, 1984, Kader 1998).

A germination test is composed of four replicates of 100 seeds that have been randomly selected and are representative of the seed lot being tested. Proper sampling cannot be over-emphasized – the test result is only as good as the sample taken! The seeds are pre-treated with a soak (except Cw and some hardwoods), and generally a period of stratification. For information on species specific treatments refer to the Seed Handling Guidebook (Kolotelo *et al.*, 2001).

Table.1 Description of various parameters used to study seed germination

Germination Parameter	Symbol	Unit	Formula for Calculation	Description of Formula	Notes and Reference
Final Germination Percentage	FGP	%	FGP=Final no. of seeds germinated in a seed lot × 100		The higher the FGP value, the greater the germination of a seed population. Scott *et al.,* (1984)
Mean Germination Time	MGT	Day	$MGT=Pf\cdot x/Pf$	f=Seeds germinated on day x	The lower the MGT, the faster a population of seeds has germinated. Orchard (1977)
First Day of Germination	FDG	Day	FDG=Day on which the first germination event occurred		Lower FDG values indicate a faster initiation of germination. Kader (1998)
Last Day of Germination	LDG	Day	LDG=Day on which the last germination event occurred		Lower LDG values indicate a faster ending of germination. Kader (1998)
Coefficient of Velocity of Germination	CVG	—	$CVG=N_1 + N_2 + \cdots + Nx/100 \times N_1T_1 + \cdots + NxTx$	N=No. of seeds germinated each day, T=No. of days from seeding corresponding to N	The CVG gives an indication of the rapidity of germination. It increases when the number of germinated seeds increases and the time required for germination decreases. Theoretically, the highest CVG possible is 100. This would occur if all seeds germinated on the first day. Jones and Sanders (1987)
Germination Rate Index	GRI	(%/day)	GRI=G1/1 + G2/2 +⋯+ Gx/x	G1=Germination percentage × 100 at the first day after sowing, G2=Germination percentage × 100 at the second day after sowing	The GRI reflects the percentage of germination on each day of the germination period. Higher GRI values indicate higher and faster germination. Esechi (1994) after modification.
Germination Index	GI	—	GI=(10×n1) + (9×n2) + ⋯ + (1×n10)	n1, n2 ...n10 = No. of germinated seeds on the first, second and subsequent days until the 10th day; 10, 9 ... and 1 are weights given to the number of germinated seeds on the first, second and subsequent days, respectively	In the GI, maximum weight is given to the seeds germinated on the first day and less to those germinated later on. The lowest weight would be for seeds germinated on the 10th day. Therefore, the GI emphasizes on both the percentage of germination and its speed. A higher GI value denotes a higher percentage and rate of germination. Bench Arnold *et al.*, (1991)
Time Spread of Germination	TSG	day	TSG=The time in days between the first and last germination events occurring in a seed lot		The higher the TSG value, the greater the difference in germination speed between the ‘fast’ and ‘slow’ germinating members of a seed lot. Kader (1998)

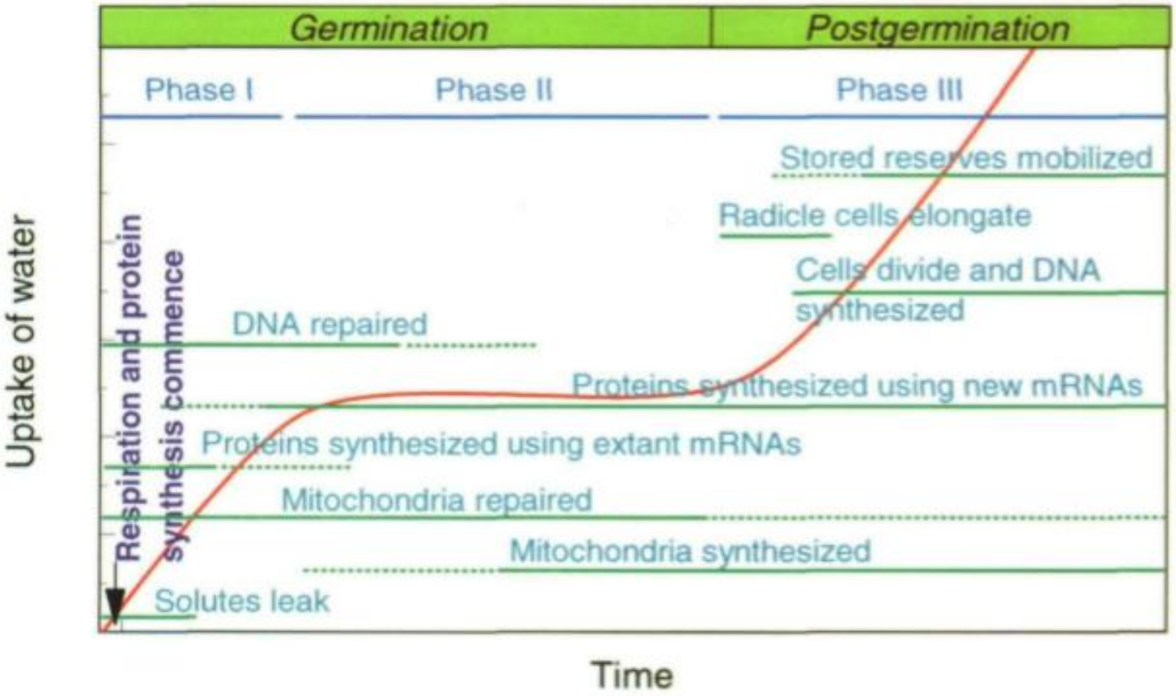


Figure 1. Time Course of Major Events Associated with Germination and Subsequent Postgerminative Growth.

The time for events to be completed varies from several hours to many weeks, depending on the plant species and the germination conditions.

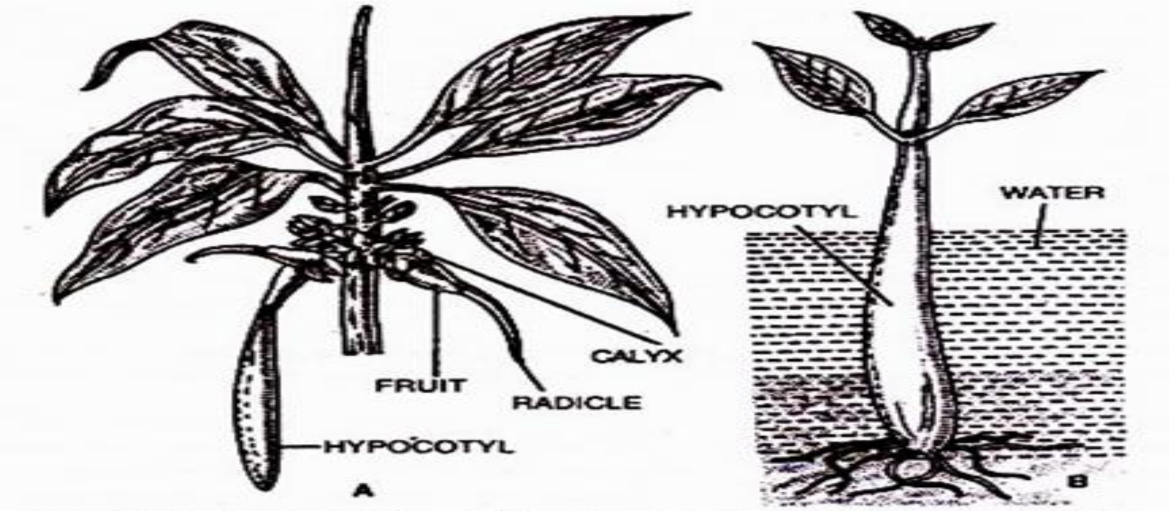


Fig. 4.9. Vivipary. A. twig of *Rhizophora* showing viviparous germination. B. A seedling has become established on tidal soil.

The result is measured in terms of the extent to which seeds have germinated (the final germination percentage attained) and the speed with which the germination process has ended. Frequently, though, other parameters represent significant factors from agronomic, planning or physiological perspectives (Jones and Sanders, 1987; Esechie 1994, Kader *et al.*, 1998; Kader, 1998; Kader *et al.*, 1999; Kader, 2005).

The length of time elapsed between the first seed to germinate and the last, the variation in germination speed and the timing that the majority of seeds germinate all have impacts on diverse cultural operations like fertilizing, harvesting and field maturity of crops (Roberts, 1981; Washitani and Saeki, 1986; Kader and Jutzi, 2001). ‘High’ (the time at which the majority of seeds germinate) and ‘low’ (the time at which the minority of seeds germinate) (Kader *et al.*, 1998) germination events are also important indicators of seed vigour and stress resistance (Kader and Jutzi, 2002). These data, from an experimental standpoint, also have a significant impact on statistical analyses (Bland and Altman 1995, Legendre and Legendre 1998, Johnson 1999).

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 agro-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(James .C and Delouche,1979).

Summary and Conclusion are as follows:

Germination is the crucial and final event in the life a seed. It can be defined as the resumption of active growth of the embryonic axis. Germination as part of plant's life history strategy, it is an irreversible biological process: Once germination has started the embryo is committed irrevocably to growth or death .Generally, in order for the seeds of a species to germinate, they must be in suitable environmental conditions "germination niche" which usually favour the growth and establishment of the seedlings. A seed requires moisture, a favorable temperature, oxygen and light for germination. Rehydration of the seed sets in motion a chain of reactions which provide the energy building blocks for the resumption of active growth and development of the young seedling. Germination failure is caused by many factories and conditions.

The process of seed germination includes imbibition, respiration, effect of Light on Seed germination, mobilization of reserves during Seed germination and role of growth regulators and development of embryo axis into seedling. In the germination process, the seed's role is that of a reproductive unit; it is the thread of life that assures survival of all plant species. Furthermore, because of its role in stand establishment, seed germination remains a key to modern agriculture.

Thus, especially in a world acutely aware of the delicate balance between food production and world population, a fundamental understanding of germination is essential to crop production**.**

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