Drought is an environmental condition affecting physiological processes. According to Maximov (1929) "the capability to endure without injury an intense loss of water is one of the most important properties of true drought resistant plants". Meyer (1932) and Stocker et al., (1943) defined the term as "the capacity of a plant to develop normally in dry habitats yielding maximum crop". Recently Stocker (1961) suggests two categories of drought resistance:

I. Protoplasmic drought resistance, i.e. ability to remain alive at a low water potential; and

II. the ability to maintain protoplasm at a higher water potential than that of the atmosphere.

The first category is equivalent to true drought resistance of Maximov and the second "to drought avoidance" by means of special physiological and morphological attributes.

The latest reviews on drought resistance define it as "the capacity of surviving through periods of drought with little or no injury".

The term drought has been divided into two broad categories:
(a) Atmospheric drought: The characteristics of atmospheric drought are, high temperature, low humidity, high light intensity and high wind velocity which favour high transpiration rates. These weather conditions are so severe that the loss of water through transpiration cannot be made good by absorption through roots even if the moisture content in the soil is adequate. Wilting due to atmospheric drought is usually temporary ("transient wilting").

(b) Soil drought: Plants suffer from soil drought when moisture in the soil is less than what is required for their growth and survival. Soil drought is comparatively more injurious to plants because often it results into permanent wilting.

The most disastrous of all is a combination of both kinds of drought, which may occur during the dry hot weather, when the soil has lost most of the water available to the plant.

In India nearly one-third of the total cultivable area is situated in the low rainfall zone, and with all the irrigational facilities at our command it may not be possible to irrigate more than 60 per cent of the total cultivable land. While application of dry-farming techniques deserve prior consideration in improvement of rainfed agriculture, choice of crops or varieties in context with their drought
resisting properties is of great significance.

The problem of drought resistance in plants has been studied by a number of workers (Maximov, 1929; Levitt, 1951; Iljin, 1957; Stocker, 1961; Chinoy 1947-1962) along several lines and many views have been put forward. Studies undertaken with a view to correlating drought resistance with water requirement as well as with various physiological and biochemical processes in the cell have been dealt with much more thoroughly in the following pages.

1. Water requirement and drought resistance:

Protoplasm in the resting stage has the ability to become air-dry without loss of life as is seen in the case of seeds, spores and other reproductive bodies. This ability of maintaining life in air-dry condition is retained for some time in seedling or spore growth. Protoplasm can tolerate deficiency of water in varying degree depending upon numerous factors. Rabe (1905) has shown that among seedlings, the Gramineae are most hardy, those from oily seeds less so and legumes least. In general most growing plants are killed by a loss of 40 to 90% of their normal water content (Schröder, 1909; Höfler, 1942).

Briggs and Shantz (1913, 1914) used the "water requirement" of a plant as an index to its drought resistance. They showed that drought resistant plants were characterized not by a low water requirement as was believed earlier
but by a high water requirement as shown by typical xerophytic plants. Klesselbach (1926) working on corn, wild alfalfa, sunflower, alfalfa, wheat, oat, sorghum also found no correlation between water requirement of these plants and their drought resistance.

The problem of water requirement of crop plants is important because deficiency of water in the plant profoundly alters metabolism, leading to unsatisfactory growth and development and lower yield of crop. To know the beginning of water deficiency in plants various physiological properties such as cellular suction pressure, concentration of cellular sap, osmotic pressure and degree of stomatal opening have been used for field purposes (Petinov, 1954; Tech. et al., 1967). Thus, it becomes possible to supply water in accordance with the water requirement of plants without causing them to wither and without making the expenditure of water too high.

2. Physiological and biochemical processes in relation to drought:

The structural peculiarities of plants such as deep and wide spreading root systems, efficient conducting systems, smaller leaf area, thick cuticle, shedding of leaves, structure of stomata, cell size and other xeromorphic characters are simply meant to postpone the adverse effects of drought and therefore, drought
resistance of plants depends on the degree of hydration which their protoplasm can endure. Hence it becomes necessary to investigate the relationship of drought resistance with the biochemical and physiological aspects of the protoplasm.

(i) Carbohydrate metabolism in relation to drought: Many investigators observed that starch disappears from wilted leaves following decrease in soil moisture (Lundegårdh, 1914; Molisch, 1921; Horn, 1923; Ahrns, 1924; Iljin, 1927; Magness et al., 1932; Schneider et al., 1941). Many others have reported an increase in sugar content on exposure to drought (Rosa, 1921; Iljin, 1929; Clements, 1937a; Miller, 1939; Julander, 1945; Subbotina, 1961). Increases in insoluble as well as soluble carbohydrate contents during drought period have also been shown by several other workers (Clements, 1937, 1937a; Grandfield, 1943; Eaton and Ergle, 1948). Iljin (1929) further showed that when plants were grouped ecologically, their sugar content increased with the dryness of habitat.

Dryness stimulated the activity of amylase and phosphorylase in cells of the leaf and hence sugar content increased. Thus the loss of water intensified decomposition and inhibited assimilation.

The accumulation of carbohydrates depends upon numerous factors and Iljin (1957) is of the view that it is not possible to state that water loss induces
the breakdown and disappearance of starch in all parts of the plant, but it can be said to be taking place in the leaves of majority of plant species.

(ii) Protoplasmic colloids in relation to drought: Colloids, particularly gels, bind water by hydrogen bonds and thus possess the ability to reduce free water. This bound-water which is strongly held in hydration bonds does not act as liquid water for it does not freeze or evaporate at temperatures at which free water freezes or evaporates. Newton and Martin (1930), and Calvert (1935) working with wheat found a correlation between bound-water content and drought resistance, whereas Whitman (1941) found no such correlation in grasses. This hypothesis of drought resistance based upon absorption of bound-water by colloids has been supported by other workers also (Traub, et al., 1946; Duisberg, 1952).

According to Levitt (1951) the lack of consistent correlation between bound-water content and drought resistance is due to the measurement of water content of the tissue as a whole and not of protoplasmic bound-water. He suggested (1959) a method for the determination of bound-water which does not involve extraction of the tissue sap.

According to Stocker (1947) the water deficiency brings about a lowering of the chemical potential of water which alters the structure of the protoplasm.
Enzymes consisting of macromolecules of folded polypeptide chains are connected by bonds of different kinds in which hydrogen and water bridges play an important role. Hydration protects the stability of the bridges and hence of the protoplasmic structure. Decrease in cell moisture diminishes hydration and thus loosens or breaks certain bond bridges. The framework of the protoplasm thus becomes loose, permeability increases and structural viscosity diminishes.

Later on Stocker explained drought resistance as a gel-sol transformation of protoplasmic colloids under the effect of desiccation which increased the uptake of divalent cations like Ca or Mg. It has been shown for Wheat and other cereals (Chinoy and Nanda, 1950, 1952; Chinoy, 1962) that under wilting treatment at the shooting and flowering stages leaves are the first to be damaged by drought followed by the stem and then the young spike. With the initiation of the shooting stage a rapid transfer of K, N and P takes place from leaves to the elongating stem and the developing spike. Hence it seems that the cells of stem are able to resist desiccation to a greater degree than those of leaves inspite of the considerable increase in the concentration of monovalent ions like K which takes place in the protoplasmic colloids of stem cells with the initiation of shooting. Thus the work of Stocker is not supported by this investigation.

Stocker's postulate that there is a reduction in the permeability of drought hardened cells to water has also
received little support. Drought hardened plant material has usually shown a greater avidity of cells for water so much so that hardened seeds germinated on a dry filter paper even in a comparatively low vapour pressure of the surrounding air, whereas untreated seeds did not germinate at all under comparable conditions (Chinoy, 1957; Shakti Gupta, 1957). Whiteside (1941) and Levitt and Scarth (1936) also reported a considerable increase in the permeability of Wheat cells under drought.

Stocker's observation of reduction in the hydration of protoplasmic colloids under drought, resulting in their increased viscosity is also at variance with that of Todd and Levitt (1951) who found a marked increase in bound water content of *Aspergillus niger* under high osmotic tension. Experiments of Chinoy (1957) and Shakti Gupta (1957) have also shown that greater hydration is brought about by drought hardening in plants. Maximov first demonstrated that a plant possesses an ability to tolerate permanent wilting mainly due to greater permeability and hydration of its protoplasmic colloids. These observations of Maximov have been confirmed not only for drought resistance (Levitt, 1951; Chinoy, 1957; Shakti Gupta, 1957) but also for salt resistance (Burygin, 1952; Shakov, 1952, Sergeiev, 1953) and also frost resistance (Levitt, 1941; Tumanov, 1940, 1951), thus proving that there is a close relationship between drought, salt and frost resistance.
Drought resistance and enzymatic activity: The investigations on the shift of enzymatic processes in wilting plants have been carried out by Sizakyan (1938 to 1940). Later on Sizakyan and Kobaikova (1947) working with wheats of varied drought resistance and also with sugar beet and pea, found that when the tissues attained a certain degree of dehydration, the protoplasmic structures lost their ability to bind the enzymes (invertase and others) and as a result the enzymes went into solution and stimulated hydrolytic decomposition. This occurred in drought resistant plants only under conditions of high water loss. Drying stimulated the activity of amylase (Spoehr et al., 1939; Shakti Gupta, 1957) and phosphatase (Sizakyan, 1940).

Recently the sulfhydryl-disulphide hypothesis formulated by Levitt (1962) for the explanation of frost resistance in plants was found to be equally applicable to drought resistance (Gaff, 1966). Levitt proposed that injury was due to an unfolding and therefore, a denaturation of the protoplasmic proteins.

Relationship of drought resistance to growth and development: Drought resistance of seedlings decreases with the progress of development (Rabe, 1905; Milthorpe, 1950). Younger tissues in a plant are more resistant to drought than the older ones (Rabe, 1905). Pringsheim (1905) has, however, shown that a movement of water takes place from older to younger parts on wilting
which protects the younger tissues longer and permits them to develop further. Christ (1911), Tumanov (1930) and Clements (1937) have observed this phenomenon in various plants. Thus it cannot be said that younger tissues are more resistant to drought so long as they are still attached to older tissues. Recently it has been shown that well-ripened, one to two year old leaves of evergreens are more drought resistant than both younger and overage leaves (Pisek and Larcher, 1954).

Chinoy (1960-62) studied the response of a number of Wheat varieties to re-watering, after permanent wilting over a number of days, at various growth stages. All the varieties showed considerable resistance to drought at tiller initiation stage by recovering completely and giving a slightly higher yield than the normally watered plants. On the other hand, wilting during the shooting and flowering stages reduced growth and yield considerably.

Asana and his co-workers (Asana, Mani, Pillay and Gahlot, 1955; Asana and Mani, 1958) working with early and early-medium varieties in pot as well as field culture have pointed out that in view of the complex effects of drought on growth and development, it may prove more profitable to examine in the first instance the effect of drought on characters directly related to yield. These investigators studied the relation of yield of Wheat with three characters namely, ear number, grain number per ear and 1000 grain-weight under normal
water supply and drought and found that under normal water supply ear number had the most potent influence on yield, whereas under drought, grain number per ear, and sometimes 1000 grain-weight were as effective as ear number.

Shcherbakov (1963) has shown that continuous cultivation of spring wheat under arid conditions leads to the formation of a new ontogenetical rhythm in its physiological and biochemical processes. This new rhythm is distinguished by a rise in physiological activity in the early growth stages and a relatively sharp decline in the succeeding period.

A reinforcement of the physiological activity in the early phases of development is the physiological basis for the accelerated rate of development of wheat and consequently, for its early ripening. Hence, it follows that for the resistance of spring wheat to drought a high rate of metabolism is a characteristic feature, not throughout its growth period, but during the first half of its growth period only.

(v) Drought resistance and ascorbic acid: It has been shown that ascorbic acid is the transformation product of sugar (Moldtmann, 1939; Loewus, 1959). According to Isherwood and Mapson (1962) the actual concentration of ascorbic acid in the tissue at any given time represents the excess formed in synthesis over that used in metabolism and most of the external factors studied affected synthesis rather than the process of utilization.
Tombesi (cited from Stocker, 1956) noticed that ascorbic acid content decreased in plants, grown under dry conditions. Ascorbic acid content increased slightly in plants growing under moderately dry conditions (50 per cent field capacity) but in extreme cases (25 per cent field capacity) it attained considerably high levels (Stocker, 1956).

Recently Chinoy et al., (1968) found that free ascorbic acid increased significantly in desiccated barley seedlings whereas the bound ascorbic acid decreased under desiccation. In the revived seedlings the reverse trend was noticed. From this, it has been suggested that increase in the concentration of free ascorbic acid during desiccation stimulated hydrolytic activity of amylase and lipase most probably by creating a reductive environment.

3. **Pre-sowing hardening treatment for induction of drought resistance:**

There is sufficient evidence available to show that drought resistance of plants can be considerably increased by subjecting seeds to a cycle of wetting and drying prior to sowing. This was first suggested by
Genkel and Kolotova (1934). The data and conclusions from a large series of experiments were published in Genkel's major work of 1946 and since then this topic has attracted much interest and stimulated many investigations in the U.S.S.R. (Genkel, 1961) and other parts of the world.

According to Genkel (1946, 1961) presowing hardening treatment affects the physico-chemical properties of the protoplasm - the greater hydration of the colloids, the higher viscosity and elasticity of the protoplasm, the greater amount of bound water and the more intense metabolism. As a result of these changes greater xeromorphic structure, lower water deficit, ability to retain greater quantity of water and a more efficient root system is produced. He further suggests that the pre-sowing hardening treatment leads to an increase in the hydrophilic colloids and a decrease in the lipophilic colloids, a decrease in the isoelectric point of the proteins (from pH 3.5 to pH 2.7) and an increase in the temperature required for coagulation of the proteins.

It has been shown from energy relationships (Milthorpe, 1959) that the water-retaining capacity of protoplasmic colloids can exert no effective influence on the water-retaining capacity of a leaf. If the rate of transpiration increases in comparison to absorption the only alternative the plant has, is to reduce the rate of transpiration by stomatal closure. Inspite of this the higher proportion of cell walls associated with
the smaller cells of hardened plants, particularly if the permeability of the plasmalemma is also decreased, could assist the hardened plants in withstanding a transient water deficit (May and Milthorpe, 1962).

These cytoplasmic changes are held by Genkel to be responsible for the lower water deficit and higher water contents of hardened plants than of control plants determined at the same time and place. Generally, increases in yield of the order of 10-25\% were obtained although much greater differences have been recorded, and, at times, no responses have been found.

Chinoy (1942, 1947) working on pre-sowing hardening treatment in Wheat varieties found that the pretreatments accelerated the rate and percentage of germination of seeds, seedling growth and flowering. He further showed that all the above characteristics of the pre-treated plants were highly significant. In another experiment (1947a) seed pretreatments were given with different concentrations of NaCl, CaCl\(_2\), \(\text{Na}_2\text{B}_4\text{O}_7\), KCl, KNO\(_3\) and \((\text{NH}_4)\text{}_2\text{SO}_4\) solutions as well as high temperature treatments. The beneficial effects of pre-treatments were observed in earlier germination, faster seedling growth rate, earlier flowering and increased yield of plants.

Chinoy further tried the effect of alternate soaking and drying of seeds and obtained an average yield of 948 lb. per acre from the treated seeds as against 866 lb. per acre from the untreated seeds on dry land over a period of three years.
Parija et al., (1945) working on paddy seeds came to a similar conclusion. Pretreated plants had higher weight of the shoot and better grain yield. The hardened plants had a lesser rate of transpiration than the untreated ones and required less water for the same amount of dry matter produced. Again the pretreated seeds not only recovered earlier from drought but also resisted drought better than the untreated plants.

Koller et al., (1962) found that the repeated cycles of imbibition and drying had a favourable effect on the subsequent rate of germination and seedling vigour which is correlated with increased water absorbing capacity probably caused by an increased amylase activity. Singh et al., (1968) observed that pretreatment with boric acid had a beneficial effect upon germination of rice and further enhanced the capacity of plants to withstand drought.

Subjecting the seeds to an alternate cycle of wetting and drying also increases the resistance of the plant to heat (Petinov and Molotovsky, 1961) and its tolerance to soil salinity (Strogonov, 1959). The heat and drought resistance of plants is considerably increased by soaking the seed in a 0.25% solution of calcium chloride for 20 hours or in solutions of boron (Genkel, 1961; Singh, et. al., 1968). Application of thiols also enhances drought tolerance in plants (Paricha and Levitt, 1967).
Zubenko (1959) obtained a 40% increase in total above-ground growth and 33% increase in grain yield from maize soaked for 24 hours and dried in two stages. Soaking for longer periods seriously reduced the percentage germination. Mart'yanova (1960) found between 16 and 55% increase in the yield of barley, grown under the usual farming conditions, in three successive years, the growth and yield of hardened plants being greatest in a year with a severe drought in May (at the beginning of "plant development").

Presowing treatment with microelements such as Cu, Mn, Zn and their mixture favourably affects the growth, yield and leaf composition in barley (Das and Shrivastava, 1965). Moreover, the uptake of N, P and K is also significantly affected. John and Jani (1968) also showed the beneficial effect of pretreatment with ascorbic acid on salt and drought resistance in barley. Their work demonstrated the beneficial effect in growth as well as developmental characters consistently in all the three varieties studied.

4. The evaluation of drought resistance of plants:

The methods developed so far for determining the drought resistance of plants are briefly considered here.

Skazkin (1934) determined the absorbing capacity of seeds, while other workers (Sizakyan, 1938, 1940; Sizakyan and Kobaikova, 1947) determined changes in enzymatic processes in plants that had suffered drought.
Several investigators tried to evaluate drought resistance by noting the rate of germination and embryo growth under conditions of limited water supply (Semakin, 1937; Shakti Gupta, 1957); by germinating seeds in salt solutions (Sergeiev, 1937; Sergeiev and Lebedev, 1937; Chinoy, 1947) and also by noting the electromotive force in germinating seeds (Niznikov, 1939). According to these investigators drought resistance of a plant remains unaltered during the entire growth period. Many workers used water requirement of a plant as an index to its drought resistance (Messelbach, 1916, 1926; Briggs and Shantz, 1913, 1914; Bayles et al., 1937; Livingstone, 1927; Maximov, 1926; Paltridge and Mair, 1936; Petinov, 1954; Petinov and Prusakova, 1955c; Petinov, 1955; Petinov and Pavlov, 1955b; Petinov and Kharanyan, 1956; Petinov and Lebedev, 1955a). Some investigators (Paltridge and Mair, 1936; Hunter et al., 1936; Kenway and Peto, 1939; Aamodt, 1935; Dexter, 1942; Platt and Darroch, 1942; Mueller and Weaver, 1942; Carroll, 1943) determined drought resistance of plants on the basis of injury caused to seedlings by subjecting them to the effect of a current of hot air in specially designed machines.

Study of nature, size and depth of the root system has also been used to determine drought resistance (Cannon, 1911; Evans, 1937; Haber, 1938; Conrad and Veihmeyer, 1929). Number and size of stomata and vascular bundles as well as osmotic pressure have also been studied for determination of drought resistance (Haber, 1938; Pavlov, 1930). Some workers (Medvedev,
1937, Asana and Mani, 1950, 1955; Ashby and May, 1941) determined the rate of photosynthetic activity and growth. Various external and internal factors influencing the drought resistance of a plant at different stages of its growth and development are not taken into consideration by these methods and hence they are of limited value.

A better method for the study of drought resistance has been found to be the direct agrophysiological test (Zablouda, 1940; Saks, 1939, 1941; Ersov, 1939; Chinoy, 1947). But the complex problem of drought resistance cannot be fully elucidated solely by this method. Drought resistance of plants is their capacity to endure wilting (Maximov, 1929). Tumanov's method of permanent wilting is based on this conception in which it has been shown that repeated wilting resulted in a "hardening" of the plant tissues similar to that observed at low temperature. Various pre-sowing hardening treatments have been formulated on the basis of this observation (Rosa, 1921; Genkel and Kolotova, 1939; Genkel, 1938; Repin and Tiskov, 1940; Smirnova et al., 1938; Semakin, 1937; Isip, 1940; Chinoy, 1947a, 1967; Genkel, 1956; Shakti Gupta, 1957). The method of wilting as developed by Tumanov (1927) depends on the survival value i.e. the number of plants surviving after the termination of the stage of permanent wilting.

Levitt, Sullivan and Krull (1960) have suggested that drought resistance may be estimated by the time required to produce 50 per cent killing of de-rooted shoots at
15 per cent relative humidity and 30°C temperature. According to them this measurement will give an estimate of resistance to loss of water and of tolerance to decrease in water content.

Chinoy (1947-61) has modified Tumanov's method of permanent wilting giving the wilting treatment at definite growth stages like tiller initiation, shooting, flowering, etc., and studying the revival of plants in terms of growth, metabolism and yield of plants.