Fundamentals of Agronomy

S.K. Dutta
A. Roychowdhury
S.S. Acharya
Seema
S.K. Pathak

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Chapter 1

Agronomy and its scope

Agriculture:

The term Agriculture is derived from two Latin words "ager" or "agri" meaning soil and "cultura" meaning cultivation. Agriculture is an applied science which encompasses all aspects of crop production including horticulture, livestock rearing, fisheries, forestry, etc. Agriculture is defined as an art, science and business of producing crops and livestock for economic purposes.

As an art, it embraces knowledge of the way to perform the operations of the farm in a skillful manner, but does not necessarily include an understanding of the principles underlying the farm practices.

As a science, it utilizes all technologies developed on scientific principles such as crop breeding, production techniques, crop protection, economics etc. to maximize the yield and profit. For example, new crops and varieties developed by hybridization, Transgenic crop varieties resistant to pests and diseases, hybrids in each crop, high fertilizer responsive varieties, water management, herbicides to control weeds, use of bio-control agents to combat pest and diseases etc.

As the business: As long as agriculture is the way of life of the rural population production is ultimately bound to consumption. But agriculture as a business aims at maximum net return through the management of land labour, water and capital, employing the knowledge of various sciences for production of food, feed, fibre and fuel. In recent years, agriculture is commercialized to run as a business through mechanization.

Agronomy:

The word agronomy has been derived from the two Greek words, ***agros*** and ***nomos*** having the meaning of **field** and **to manage,** respectively. Literally, agronomy means the "art of managing field". Technically, it means the "science and economics of crop production by management of farm land".

Agronomy is the art and underlying science in production and improvement of field crops with the efficient use of soil fertility, water, labourer and other factors related to crop production. Agronomy is the field of study and practice of ways and means of production of food, feed and fibre crops. Agronomy is defined as "a branch of agricultural science which deals with principles and practices of field crop production and management of soil for higher productivity.

Importance:

Among all the branches of agriculture, agronomy occupies a pivotal position and is regarded as the mother branch or primary branch. Like agriculture, agronomy is an integrated and applied aspect of different disciplines of pure sciences. Agronomy has three clear branches namely Crop Science, Soil Science and Environmental Science that deals only with applied aspects. Agronomy is a synthesis of several disciplines like crop science, which includes plant breeding, crop physiology and biochemistry etc., and soil science, which includes soil fertilizers, manures etc., and environmental science which includes meteorology and crop ecology.

Basic Principles of Agronomy

• Planning, programming and executing measures for maximum utilization of land, labourer, capital and other factors of production.

• Choice of crop varieties adaptable to the particular agro-climate, land situation, soil fertility, season and method of cultivation and befitting to the cropping system;

• Proper field management by tillage, preparing field channels and bunds for irrigation and drainage, checking soil erosion, leveling and adopting other suitable land improvement practices;

• Adoption of multiple cropping and also mixed or intercropping to ensure harvest even under adverse environmental conditions;

• Timely application of proper and balanced nutrients to the crop and improvement of soil fertility and productivity. Correction of ill-effects of soil reactions and conditions and increasing soil organic matter through the application of green manure, farm yard manure, organic wastes, bio fertilizers and profitable recycling of organic wastes;

• Choice of quality seed or seed material and maintenance of requisite plant density per unit area with healthy and uniform seedlings;

• Proper water management with respect to crop, soil and environment through conservation and utilization of soil moisture as well as by utilizing water that is available in excess, and scheduling irrigation at critical stages of crop growth.

• Adoption of adequate, need-based, timely and exacting plant protection measures against weeds, insect-pests, pathogens, as well as climatic hazards and correction of deficiencies and disorders;

• Adoption of suitable and appropriate management practices including intercultural operations to get maximum benefit from inputs dearer and difficult to get, low-monetary and non-monetary inputs;

• Adoption of suitable method and time of harvesting of crop to reduce field loss and to release land for succeeding crop(s) and efficient utilization of residual moisture, plant nutrients and other management practices;

• Adoption of suitable post-harvest technologies.

• Agronomy was recognized as a distinct branch of agricultural science only since about since about 1900. The American Society of Agronomy was organized in 1908.

Irrigation management: Whether to irrigate continuously or stop in between and how much water should be irrigated are calculated to find the water requirement.

• Crop planning (*i.e.*,) developing crop sequence should be developed by agronomist (*i.e.*) what type of crop, cropping pattern, cropping sequence, etc.

• Agronomists are also developing the method of harvesting, time for harvesting, etc. The harvest should be done in the appropriate time.

• Decision-making in the farm management. What type of crop to be produced, how much crop, including marketing should be planned? Decision should be at appropriate time.

Chapter 2

Seeds and sowing

Seed – Seed is an embryonic part covered in a seed coat often containing some food. It is formed from the ripened ovule of a plant after fertilization.
Grain – A grain is a small edible fruit usually hard on the outside, harvested from crops. Grains basically grow in a cluster on top of the mature plant.

Seed vs Grain –
1. A seed is an ovule containing an embryo while a grain is a fusion of the seed coat and the fruit.
2. Typically seeds are planted to grow plants while grains are harvested for food.
Grains provide food from the fruit part while seeds mainly food from embryo part.

Seeds are the vital part of agriculture. Selection of good quality seeds is a challenge for famers. Only good quality seeds which are sown properly can give an expected result or yield. Seeds of variety of types and strains are available; cultivators have to choose from these and these have to be sown in the field.

Seed Selection

Healthy, good quality seeds are the root of a healthy crop. Hence selection of seeds is crucial. Selection helps to obtain healthy seeds; sustain and optimize the quality of crop strain. Based on plant size, quantity of grains, fruit size or colour, disease resistance etc. seeds can be selected. Farmers also need to check the germination period, nutrients required so that the selected seeds will be beneficial in terms of yield and finance. Some seeds are sources of diseases; they can be used after proper treatment like chemical or hot water treatments etc. A careful observation of crops and their yield in first year may help farmers to choose best strains of seeds for successive years. Hence for high yield, sow best seeds.

Classification:

Breeder Seed

Breeder seed is the progeny of nucleus seed of a variety and is produced by the originating breeder or by a sponsored breeder. Breeder seed production is the mandate of the Indian Council of Agricultural Research, State Agricultural Universities, Sponsored breeders recognized by selected State Seed Corporations, and Non-governmental Organizations.

Foundation Seed

Foundation seed is the progeny of breeder seed and is required to be produced from breeder seed or from foundation seed which can be clearly traced to breeder seed. The responsibility for production of foundation seed has been entrusted to the NSC, SFCI, State Seeds Corporation, State Departments of Agriculture and private seed producers, who have the necessary infrastructure facilities. Foundation seed is required to meet the standards of seed certification prescribed in the Indian Minimum Seeds Certification Standards, both at the field and laboratory testing.

Certified Seed

Certified seed is the progeny of foundation seed and must meet the standards of seed certification prescribed in the Indian Minimum Seeds Certification Standards, 1988. The production and distribution of quality/certified seeds is primarily the responsibility of the State Governments. Certified seed production is organized through State Seed Corporation, Departmental Agricultural Farms, Cooperatives etc.

Methods of Sowing

Seeds are sown directly in the field (seed bed) or in the nursery (nursery bed) where seedlings are raised and transplanted later. Direct seeding may be done by Broadcasting, Dibbling, Drilling, Sowing behind the country plough, Planting and Transplanting.

(*a*) ***Broad casting*** **-** Broad casting is the scattering or spreading of the seeds on the soil, which may or may not be incorporated into the soil. Broadcasting of seeds may be done by hand, mechanical spreader or aeroplane. Broadcasting is the easy, quick and cheap method of seeding. The difficulties observed in broadcasting are uneven distribution, improper placement of seeds and less soil cover and compaction. As all the seeds are not placed in uniform density and depth, there is no uniformity of germination, seedling vigour and establishment. It is mostly suited for closely spaced and small seeded crops.

(*b*) ***Dibbling*** **-** It is the placing of seeds in a hole or pit made at a predetermined spacing and depth with a dibbler or planter or very often by hand. Dibbling is laborious, time consuming and expensive compared to broadcasting, but it requires less seeds and, gives rapid and uniform germination with good seedling vigour.

(*c*) ***Drilling*** **-** It is a practice of dropping seeds in a definite depth, covered with soil and compacted. Sowing implements like seed drill or seed cum fertilizer drill are used. Manures, fertilizers, soil amendments, pesticides, etc. may be applied along with seeds. Seeds are drilled continuously or at regular intervals in rows. It requires more time, energy and cost, but maintains uniform population per unit area. Rows are set according to the requirements.

(*d*) ***Sowing behind the country plough*** **-** It is an operation in which seeds are placed in the plough furrow either continuously or at required spacing by a man working behind a plough. When the plough takes the next adjacent furrow, the seeds in the previous furrow are closed by the soil closing the furrow. Depth of sowing is adjusted by adjusting the depth of the plough furrow. *e.g.*, ground nut sowing in dry land areas of Tamil Nadu.

(*e*) ***Planting*** **-** Placing seeds or seed material firmly in the soil to grow.

(*f*) ***Transplanting*** **-** Planting seedlings in the main field after pulling out from the nursery. It is done to reduce the main field duration of the crops facilitating to grow more number of crops in an year. It is easy to give extra care for tender seedlings. For small seeded crops like rice and ragi which require shallow sowing and frequent irrigation for proper germination, raising nursery is the easiest way.

Pre-monsoon sowing:

Normally, sowing is taken up after receipt of sufficient amount of rainfall (20 mm) in the case of dry land farming. Since sowing is continued for two or three days after a soaking rain, certain amount of moisture is lost during the period between the receipt of rainfall and sowing. In the case of heavy clay soils (black soils), sowing operation is difficult after the receipt of rain. To overcome this difficulty, sowing is taken up in dry soil prepared with summer rains, 7-10 days before the anticipated receipt of sowing rains. The seeds germinate after the receipt of the rainfall. This method of sowing is known as dry sowing or pre-monsoon sowing. By this method, the entire rainfall received is efficiently utilized.

Factors involved in Sowing Management

This can be classified into two broad groups.

1. **Mechanical factors -** Factors such as depth of sowing, emergence habit, seed size and weight, seedbed texture, seed–soil contact, seedbed fertility, soil moisture etc.

(*i*) ***Seed size and weight*:** Heavy and bold seeds produce vigorous seedlings. Application of fertilizer to bold seed tends to encourage the seedlings than the seedlings from small seeds.

(*ii*) ***Depth of sowing*:** Optimum depth of sowing ranges from 2.5–3 cm. Depth of sowing depends on seed size and availability of soil moisture. Deeper sowing delays field emergence and thus delays crop duration. Deeper sowing sometimes ensures crop survival under adverse weather and soil conditions mostly in dry lands.

(*iii*) ***Emergence habit*:** Hypogeal seedlings may emerge from a relatively deeper layer than epigeal seedlings of similar seed size.

(*iv*) ***Seedbed texture*:** Soil texture should minimize crust formation and maximize aeration, which in turn influence the gases, temperature and water content of the soil. Very fine soil may not maintain adequate temperature and water holding capacity.

(*v*) ***Seeds–Soil contact*:** Seeds require close contact with soil particles to ensure that water can be absorbed readily. A tilled soil makes the contact easier. Forming the soil around the seed (broadcasted seeds) after sowing improves the soil–seed contact.

(*vi*) ***Seedbed fertility*:** Tillering crops like rice, ragi, bajra etc., should be sown thinly on fertile soils and more densely on poor soils. Similarly high seed rate is used on poor soil for non-tillering crops. Although higher the seed rate grater the yield under conditions of low soil fertility, in some cases such as cotton, a lower seed rate gives better result than a higher seed rate.

(*vii*) ***Soil moisture*:** Excess moisture in soil retards germination and induce rotting and damping off disease except in swamp (deep water) rice. Adjustment in depth is made according to moisture conditions, *i.e.*, deeper sowing on dry soils and shallow sowing on wet soils. Sowing on ridges is usually recommended on poorly drained soils.

2. **Biological factors -** Factors like companion crops, competition for light, soil microorganisms etc.

(*i*) ***Companion crop*:** Companion crop is usually sown early to suppress weed growth and control soil erosion. In cassava + maize/yam cropping, cassava is planted later in yam or maize to minimize the effect of competition for light. In mixed cropping, all the crops are sown at the same time.

(*ii*) ***Competition of light*:** In mixed stands, optimum spacing for each crop minimizes the competition of light.

(*iii*) ***Soil microorganisms*:** The microorganisms present in the soil should favour seed germination and should not posses any harmful effect on seeds/emerging seedlings.

Chapter 3

Tillage and Tilth

Tillage operations in various forms have been practiced from the very inception of growing plants. Primitive man used tools to disturb the soils for placing seeds. The word tillage is derived from the Anglo-Saxon words *tilian* and *teolian*, meaning to plough and prepare soil for seed to sow, to cultivate and to raise crops. Jethrotull, who is considered as Father of tillage, suggested that thorough ploughing is necessary so as to make the soil into fine particles.

Definition

Tillage refers to the mechanical manipulation of the soil with tools and implements so as to create favourable soil conditions for better seed germination and subsequent growth of crops. **Tilth** is a physical condition of the soil resulting from tillage. Tilth is a loose friable (mellow), airy, powdery, granular and crumbly condition of the soil with optimum moisture content suitable for working and germination or sprouting of seeds and propagules *i.e.*, tilth is the ideal seed bed.

Characteristics of good tilth

Good tilth refers to the favourable physical conditions for germination and growth of crops. Tilth indicates two properties of soil *viz.*, the size distribution of aggregates and mellowness or friability of soil. The relative proportion of different sized soil aggregates is known as size distribution of soil aggregates. Higher percentages of larger aggregates with a size above 5 mm in diameter are necessary for irrigated agriculture while higher percentage of smaller aggregates (1–2 mm in diameter) are desirable for rainfed agriculture. Mellowness or friability is that property of soil by which the clods when dry become more crumbly. A soil with good tilth is quite porous and has free drainage up to water table. The capillary and non-capillary pores should be in equal proportion so that sufficient amount of water and free air is retained respectively.

Objectives

Tillage is done:

• To prepare ideal seed bed favourable for seed germination, growth and establishment;
• To loosen the soil for easy root penetration and proliferation;
• To remove other sprouting materials in the soil;
• To control weeds;
• To certain extent to control pest and diseases which harbour in the soil;
• To improve soil physical conditions;
• To ensure adequate aeration in the root zone which in turn favour for microbial and biochemical activities;
• To modify soil temperature;

- To break hard soil pans and to improve drainage facility;
- To incorporate crop residues and organic matter left over;
- To conserve soil by minimizing the soil erosion;
- To conserve the soil moisture;
- To harvest efficiently the effective rain water;
- To assure the through mixing of manures, fertilizers and pesticides in the soil;
- To facilitate water infiltration and thus increasing the water holding capacity of the soil, and
- To level the field for efficient water management

Types of tilth

1. **Fine Tilth** refers to the powdery condition of the soil. **Coarse Tilth** refers to the rough cloddy condition of the soil.
2. **Fine seedbed** is required for small seeded crops like ragi, onion, berseem, tobacco. **Coarse seedbed** is needed for bold seeded crops like sorghum, cotton, chickpea, lab-lab etc.

Types of tillage

1. **On Season Tillage:** It is done during the cropping season (June–July or Sept.–Oct.).
2. **Off Season Tillage:** It is done during fallow or non-cropped season (summer).
3. **Special Types of Tillage:** It is done at any time with some special objective/purpose.

On Season Tillage

Tillage operations done for raising the crops in the same season or at the onset of the crop season are called as on season tillage. They are,

A. Preparatory Tillage

It refers to tillage operations that are done to prepare the field for raising crops. It is divided into three types *viz.*, (*i*) primary tillage, (*ii*) secondary tillage, and (*iii*) seed bed preparation.

(*i*) **Primary tillage -** The first cutting and inverting of the soil that is done after the harvest of the crop or untilled fallow, is known as primary tillage. It is normally the deepest operation performed during the period between two crops. Depth may range from 10–30 cm. It includes ploughing to cut and invert the soil for further operation. It consists of deep opening and loosening the soil to bring out the desirable tilth. The main objective is to control weeds to incorporate crop stubbles and to restore soil structure.

(*ii*) **Secondary tillage -** It refers to shallow tillage operation that is done after primary tillage to bring a good soil tilth. In this operation the soil is stirred and conditioned by breaking the clods and crust, closing of cracks and crevices that form on drying. Incorporation of manures and fertilizers, leveling, mulching, forming ridges and furrows are the main objectives. It includes cultivating, harrowing, pulverizing, raking, leveling and ridging operations.

(*iii*) **Seed bed preparation -** It refers to a very shallow operation intended to prepare a seed bed or make the soil to suit for planting. Weed control and structural development of the soil are the objectives.

B. Inter Tillage/Inter Cultivation

It refers to shallow tillage operation done in the field after sowing or planting or prior to harvest of crop plants *i.e.,* tillage during the crop stand in the field. It includes inter cultivating, harrowing, hoeing, weeding, earthing up, forming ridges and furrows etc. Inter tillage helps to incorporate top dressed manures and fertilizers, to earth up and to prune roots.

Off Season Tillage

Tillage operation is done for conditioning the soil during uncropped season with the main objective of water conservation, leveling to the desirable grade, leaching to remove salts for soil reclamation reducing the population of pest and diseases in the soils. etc. They are:

(*a*) **Stubble or Post harvest tillage -** Tillage operation carried out immediately after harvest of crop to clear off the weeds and crop residues and to restore the soil structure. Removing of stiff stubbles of sugarcane crop by turning and incorporating the trashes and weeds thus making the soil ready to store rain water etc., are the major objectives of such tillage operations.

(*b*) **Summer tillage** - Operation being done during summer season in tropics to destroy weeds and soil borne pest and diseases, checking the soil erosion and retaining the rain water through summer showers. It affects the soil aggregates, soil organic matter and sometimes favour wind erosion. It is called as Kodai uzavu in Tamil Nadu state.

(*c*) **Winter tillage -** It is practiced in temperate regions where the winter is severe that makes the field unfit for raising crops. Ploughing or harrowing is done in places where soil condition is optimum to destroy weeds and to improve the physical condition of the soil and also to incorporate plant residues.

(*d*) **Fallow tillage -** It refers to the leaving of arable land uncropped for a season or seasons for various reasons. Tilled fallow represent an extreme condition of soil disturbance to eliminate all weeds and control soil borne pest etc. Fallow tilled soil is prone to erosion by wind and water and subsequently they become degraded and depleted.

Special Types

Special type tillage includes

(*i*) **Subsoil tillage (sub soiling)** is done to cut open/break the subsoil hard pan or plough pan using sub soil plough/chisel plough. Here the soil is not inverted. Sub soiling is done once in

4–5 years, where heavy machinery is used for field operations and where there is a colossal loss of topsoil due to carelessness. To avoid closing of sub soil furrow vertical mulching is adopted.

(*ii*) **Levelling by tillage -** Arable fields require a uniform distribution of water and plant nutrition for uniform crop growth. This is achieved when fields are kept fairly leveled.

Levellers and scrapers are used for levelling operations. In leveled field soil erosion is restricted and other management practices become easy and uniform.

(*iii*) **Wet tillage -** This refers to tillage done when the soil is in a saturated (anaerobic) condition. For example puddling for rice cultivation.

(*iv*) **Strip tillage -** Ploughing is done as a narrow strip by mixing and tilling the soil leaving the remaining soil surface undisturbed.

(*v*) **Clean tillage -** Refers to the working of the soil of the entire field in such a way no living plant is left undisturbed. It is practiced to control weeds, soil borne pathogen and pests.

(*vi*) **Ridge tillage -** It refers to forming ridges by ridge former or ridge plough for the purpose of planting.

(*vii*) **Conservation tillage -** It means any tillage system that reduces loss of soil or water relative to conventional tillage. It is often a form of non-inversion tillage that retains protective amounts of crop residue mulch on the surface. The important criteria of a conservation tillage system are:

(*i*) presence of crop residue mulch, (*ii*) effective conservation of soil and water, (*iii*) improvement of soil structure and organic matter content, and (*iv*) maintenance of high and economic level of production (refer section 7.10 of this chapter).

(*viii*) **Contour tillage -** It refers to tilling of the land along contours (contour means lines of uniform elevation) in order to reduce soil erosion and run off.

(*ix*) **Blind tillage -** It refers to tillage done after seeding or planting the crop (in a sterile soils) either at the pre-emergence stage of the crop plants or while they are in the early stages of growth so that crop plants (cereals, tuber crops etc.) do not get damaged, but extra plants and broad leaved weeds are uprooted.

Factors affecting (intensity and depth of) the tillage operations

Several factors are responsible for deciding intensity and depth of tillage operations. They are soil type, crop and variety, type of farming, moisture status of the soil, climate and season, extent of weed infestation, irrigation methods, special needs and economic condition, and knowledge and experience of the farmer.

(*i*) ***Crop* -** It decides the type, intensity and depth of tillage operations with small sized seeds like finger millet, tobacco etc. Require a fine seedbed which can provide intimate soil-seed contact as against coarser seed bed required for larger size seeds such as sorghum, maize, pulses, etc. Root or tuber crops require deep tillage whereas rice requires shallow puddling.

(*ii*) ***Soil type* -** It dictates the time of ploughing. Light soils require early and rapid land preparation due to free drainage and low retentive capacity as against heavy soils.

(*iii*) ***Climate* -** It influences soil moisture content, draught required tilling and the type of cultivation. Low rainfall and poor water retentive capacity of shallow soil do not permit deep ploughing at the start of the season. Heavy soils developing cracks during summer (self tilled) need only harrowing. Light soils of arid regions need coarse tilth to minimize wind erosion.

(*iv*) ***Type of farming* -** It influences the intensity of land preparation. In dry lands, deep ploughing is necessary to eradicate perennial weeds and to conserve soil moisture. Repeated shallow tilling is adequate under such intensive cropping.

(*v*) ***Cropping system* -** In involves different crops, which need different types of tillage. Crop following rice needs repeated preparatory tillage for obtaining an ideal seedbed. Crops following tuber crops like potato require minimum tillage. Similarly crops following pulses need lesser tillage than that of following sorghum, maize or sugarcane.

Depth of ploughing

Desirable ploughing depth is 12.5–20 cm. Ploughing depth varies with effective root zone depth of the crops. Ploughing depth is 10–20 cm to shallow rooted crops and 15–30 cm to deep-rooted crops. Deep ploughing is done to control perennial weeds like *Cyanodon dactylon* and to break soil hard pans. Since deep ploughing increases the cost, most farers resort to shallow ploughing only.

Number of ploughing

It depends on soil conditions, time available for cultivation between two crops, (turn over period) type of cropping systems etc. Small or fine seeded crop requires fine tilth, which may require more ploughings. Zero tillage is practiced in rice fallow pulse crops or relay cropping system. Three numbers of puddling is sufficient for rice cultivation. Minimum numbers of ploughing are taken up at optimum moisture level to bring favourable tilth depending on the need of the crop and financial resources of the farmer. In fact, this brought the concept of minimal tillage or zero tillage systems.

Time of ploughing

The time of ploughing is decided based on moisture status and type of soil. The optimum moisture content for tillage is 60% of field capacity. Ploughing at right moisture content is very important. Summer ploughing (March–May) can be practiced utilizing summer showers to control weeds and conserve soil moisture. Light soils can be worked under wide range of moisture. Loamy soils can be easily brought to good tilth. Pulverization of clay soils is difficult as they dry into hard clods.

Method of ploughing

Ploughing aims at stirring and disturbing the top layer of soil uniformly without leaving any unploughed strips of land. Straight and uniformly wide furrows give a neat appearance to the ploughed field. When the furrows are not straight or when the adjacent furrows are not uniformly spaced, narrow strips of land are left unploughed. The correct inter furrow space is little over the width of the furrow slice. After the harvest of a crop the land is first ploughed along the length of the field. This reduces the number of turns at the headlands for opening fresh furrows. The next ploughing is done across the field for breaking furrows of the previous ploughing. This must increase the turns at the headlands and the empty turns along the headlands, but is unavoidable. New turns are taken 6 m wide each time, till the entire field is covered.

Modern concepts of tillage

In conventional tillage combined primary and secondary tillage operations are performed in preparing seed bed by using animal or tractor, which cause hard pan in sub soils resulting in poor infiltration of rain water, thus it is more susceptible to run off and soil erosion. Farmers usually prepare fine seed bed by repeated ploughing, when the animal of the farm is having less work. Research has shown that frequent tillage is rarely beneficial and often detrimental. Repeated use of heavy machinery destroys structures, causes soil pans and leads to soil erosion. Moreover energy is often wasted during tillage processes. All these reasons led to the development of modern concepts namely the practices like minimum tillage, zero tillage, stubble mulch farming and conservation tillage, etc.

1. Minimum Tillage

Minimum tillage is aimed at reducing tillage to the minimum necessary for ensuring a good seedbed, rapid germination, a satisfactory stand and favourable growing conditions. Tillage can be reduced in two ways by omitting operations, which do not give much benefit when compared to the cost, and by combining agricultural operations like seeding and fertilizer application.

(a) Advantages (especially in coarse and medium textured soils)

• Improved soil conditions due to decomposition of plant residues *in situ*.

• Higher infiltration caused by the vegetation present on the soil and channels formed by the decomposition of dead roots.

• Less resistance to root growth due to improved structure.

• Less soil compaction by the reduced movement of heavy tillage vehicles.

• Less soil erosion compared to conventional tillage.

(b) Disadvantages

• Seed germination is lower with minimum tillage.

• More nitrogen has to be added as the rate of decomposition of organic matter is slow. This point holds good only in temperate regions. Contrary to this in tropics, minimum tillage recommended to conserve organic matter in the soil.

• Nodulation is affected in some leguminous crops like peas and broad beans.

• Sowing operations are difficult with ordinary equipment.

• Continuous use of herbicides causes pollution problems and dominance of perennial problematic weeds (weed shift).

Minimum tillage can be achieved by the following methods:

(*a*) **Row zone tillage -** Primary tillage is done with mould board plough in the entire area of the field, secondary tillage operations like discing and harrowing are reduced and done only in row zone.

(*b*) **Plough-plant tillage -** After the primary tillage a special planter is used for sowing. In one run over the field, the row zone is pulverized and seeds are sown by the planter.

(*c*) **Wheel track planting -** Primary ploughing is done as usual. Tractor is used for sowing, the wheels of the tractor pulverize the row zone in which planting is done.

2. Zero Tillage/No Tillage/Chemical Tillage

Zero tillage is an extreme form of minimum tillage. Primary tillage is completely avoided and secondary tillage is restricted to seedbed preparation in the row zone only. It is also known as no-tillage and is resorted to places where soils are subjected to wind and water erosion, timing of tillage operation is too difficult and requirements of energy and labour for tillage are also too high. Weeds are controlled using herbicides. Hence, it is also referred as chemical tillage.

There are two types of zero tillage.

(*a*) **Till Planting** is one method of practicing zero tillage. A wide sweep and trash bars clear a strip over the previous crop row and planter–opens a narrow strip into which seeds are planted and covered. In zero tillage, herbicide functions are extended. Before sowing, the vegetation present has to be destroyed for which broad spectrum non-selective herbicides with relatively short residual effect (Paraquat, Glyphosate etc.) are used and subsequently selective and persistent herbicides are needed (Atrazine, Alachlor etc.).

(*b*) **Sod planting or sod culture:** Sod refers to top few centimeters of soil permeated by and held together with grass roots or grass-legume roots. Planting of seeds in sods without any tillage operation is known as sod culture or sod seeding. Usually legumes or small grains are mechanically placed directly into a sod.

Advantages

• Zero tilled soils are homogenous in structure with more number of earthworms. These soil physical properties are apparent after two years of zero tillage.

• The organic matter content increases due to less mineralization.

• Surface runoff is reduced due to the presence of mulch.

Disadvantages

• In temperate countries highest dose of nitrogen has to be applied for mineralization of organic matter in zero tillage.

• Large population of perennial weeds appears in zero tilled plots.

• Higher number of volunteer plants and build up of pests are the other problems.

1. Stubble Mulch Tillage or Stubble Mulch Farming

In this tillage, soil is protected at all times either by growing a crop or by leaving the crop residues on the surface during fallow periods. Sweeps or blades are generally used to cut the soil up to 12 to 15 cm depth in the first operation after harvest and the depth of cut is reduced during subsequent operations. When unusually large amount of residues are present, a disc type implement is used for the first operation to incorporate some of the residues into the soil.

Two methods are adopted for sowing crops in stubble mulch farming.

• Similar to zero tillage, a wide sweep and trash-bars are used to clear a strip and a narrow planter-shoe opens a narrow furrow into which seeds are placed.

• A narrow chisel of 5–10 cm width is worked through the soil at a depth of 15–30 cm leaving all plant residues on the surface. The chisel shatters tillage pans and surface crusts. Planting is done through residues with special planters.

Disadvantages

• The residues left on the surface interfere with seedbed preparation and sowing operations.

• The traditional tillage and sowing implements or equipments are not suitable under these conditions.

2. Conservation Tillage

Though it is similar to that of stubble mulch tillage, it is done to conserve soil and water by reducing their losses. Modern tillage methods are practiced in western countries especially in USA. In India, it is not suitable due to several reasons. In USA, straw and stubbles are left over in the field but in India, it is a valuable fodder for the cattle and fuel for the home. Use of heavy machinery in India is limited and therefore, problem of soil compaction is rare. The type of minimum tillage that can be practiced in India is to reduce the number of ploughings to the minimum necessary *i.e.*, unnecessary repeated ploughings/harrowing can be avoided.

Chapter 4

Crop density and geometry

Crop geometry is the pattern of distribution of plant over the ground or the shape of the area available to the individual plant, in a crop field. It also refers to the shape of the space available for individual plants. It influences crop yield through its influence on light interception, rooting pattern and moisture extraction pattern. Crop geometry is altered by changing inter and intra-row spacing (Planting pattern).

• Wider spaced crops have advantage under this geometry

• Plants which requires no restriction in all directions are given square geometry

• Usually perennial vegetations like trees/shrubs are under these arrangements.

(i) ***Square planting*** - Square arrangements of plants will be more efficient in the utilization of light, water and nutrients available to the individual plants than in a rectangular arrangement.

(ii) ***Rectangular planting*** - Sowing the crop with seed drill, wider inter-row and closer intra-row and closer intra-row spacing leads to rectangularity. Rectangular arrangement facilitates easy intercultivation. Rectangular planting mainly suits annual crops, crops with closer spacing etc., the wider section (row) is given for irrigation, intercultural operation etc.

• It is an arrangement to restrict the endless growth habit in order to switch over from vegetation to the productive phase.

• This method accommodate high density planting

• It can facilitate intercropping also.

(iii) ***Triangular planting*** - It is a method to accommodate plant density under perennial/tree crops.

(iv) ***Miscellaneous planting*** - In rice and ragi transplanting is done either in rows or at random. Skipping of every alternate row is known as skip row planting. When one row is skipped the density is adjusted by decreasing inter-row spacing. When the inter row spacing is reduced between two rows and spacing between two such pair are increased then it is known as paired row planting. It is generally done to introduce an inter crop.

Chapter 5

Crop nutrition, Manures and fertilizers

In nature there are 109 elements and out of these only 17 elements are essential. Arnon and Stout (1939) first proposed the term criteria of essentiality and later Arnon (1954) revised some of the criteria and concluded the three essential criteria.

Criteria of essentiality of nutrients:

- A mineral element is considered essential to plant growth and development if the element is directly involved in plant metabolic function.

Ex. N involved in protein synthesis, K involved in stomata opening and closing and sugar translocation. However, P involved in energy transfer

- Plants are unable to complete its lifecycle if the element is absent.
- Deficiency symptoms in the plant of the element can only be corrected by the supply of the particular element.

Seventeen elements are considered essential to plant growth. Carbon (C), Hydrogen (H) and Oxygen (O) are the structural or basic nutrient and not considered mineral nutrients but are the most abundant element sin plants. The photosynthetic process in green leaves converts CO2 and H2O into simple carbohydrates from which amino acids, sugars, proteins, nucleic acid and other organic compounds are synthesized.

The remaining 14 essential mineral elements due to their primary sources are mineral and are classified as macronutrients & micronutrients, and the classification based on their relative abundance in plants. The essential nutrients are as follows.

Essential nutrients	Type
C, H, and O	Structural or basic nutrient, but not mineral.
N, P, and K	Primary elements, macro nutrients, require larger quantity.
Ca, Mg, and S	Secondary elements, macro nutrients, require lesser quantity.
Zn, Fe, Cu, Mn	Metalic, micronutrients or trace elements, require lesser quantity.
B, Mo, Cl	Non Metalic, micronutrients or trace elements, require lesser quantity.
Ni	Metalic, micronutrient or trace element, requires lesser quantity.

- In addition to the 17 essential nutrients several elements are beneficial to some plants but are not considered necessary for completion of the plant life cycle. These are Cobalt (Co), Sodium (Na), Silicon (Si), Selenium (Se), Vanadium (V) and Aluminium (Al).
- **Cobalt (Co)** is essential for the growth of symbiotic microorganisms such as *Rhizobia*, free living N_2 fixing bacteria and blue green algae.
- **Sodium (Na)** is essential for halophytic plants that accumulate salts in vacuoles to maintain turgor and growth of the plant.
- **Silicon (Si)** has specific role in rice, sugarcane crops. It is accumulated in cell wall which strengthens the stem, prevails cop lodging and increases water use efficiency.

- **Selenium (Se)** is required by cabbage, nustard with an intermediate amount, while grasses ad grain crops absorb low to moderate amount of Se.
- **Vanadium (V)** is essential for the growth of green algae.
- **Aluminium (Al)** is not an essential plant nutrient, though in plants can be high when soil contain relatively large amount of Al.

Classification of nutrients

a. on the basis of quantity of nutrient required:

i. **Basic nutrients:** These constitute 96% of total dry matter of plant. e.g. Carbon, Hydrogen and Oxygen. Among these, carbon and oxygen constitute 45% each and hydrogen is 6%.

ii. **Macro nutrients:** The nutrients which are required by plants in large quantities are called macro or major nutrients. These are six in number like Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Sulphur, Carbon, Hydrogen and Oxygen. Macro nutrients have again two categories:
   - **Primary nutrients:** Among macro nutrients, Nitrogen, Phosphorus and Potassium are known as primary nutrients which are required in a proper ratio for a successful crop.
   - **Secondary nutrients:** Next to primary nutrients, there are three elements such as Calcium, Magnesium and Sulphur which are known as secondary nutrients.

iii. **Micro nutrients:** These nutrients required by plants in small quantities and also known as minor or trace elements. These are eight in number like Manganese, Iron, Zinc, Copper, Boron, Molybdenum Chlorine and Cobalt.

b. Classification on the basis of mobility of nutrient in the soil:

i. **Mobile nutrients:** The nutrients are highly soluble and these are not adsorbed on clay complexes. e.g., NO_3^-, SO_4^{2-},BO_3^{2-}, Cl^- and $Mn+^2$

ii. **Less mobile nutrients:** They are soluble, but they are adsorbed on clay complex, so their mobility is reduced. e.g., NH_4^+, K^+, Ca^+, Mg^{2+}, $Cu2^+$

iii. **Immobile nutrients:** Nutrient ions are highly reactive and get fixed in the soil. e.g., $H_2PO_4^-$,HPO_4^{2-}, $Zn^{2+}3$

c. Classification on the basis of mobility with in plant:

i.	Highly mobile:	N, P and K.
ii.	Moderately mobile:	Zn
iii.	Less mobile:	S, Fe, Mn, Cl, Mo and Cu
iv.	Immobile:	Ca and B

Functions of plant nutrients:

Carbon (C): It is the basic molecular component of carbohydrates, protein, lipids and nucleic acids.

Oxygen (O): It is somewhat like carbon in that it occurs in virtually all organic compounds of living organisms.

Hydrogen (H): Play a certain role in plant metabolism. Important in ionic balance and as main reducing agent plays a key role in energy relation of cells.

Nitrogen (N): Nitrogen is needed for vigorous vegetative leaf and stem growth and dark green leaf colour (chlorophyll production). It is a component of many important organic compounds ranging from protein to nucleic acid. It feeds soil microorganisms as they decompose organic matter. It is part of proteins, enzymes, chlorophyll, and growth regulators. Uptake inhibited by high phosphorus levels. N/K ratio is important: high N/low K favours vegetative growth; low N/high K promotes flowering and fruiting.

Phosphorus (P): Phosphorus is very mobile in plants; relatively immobile in soil and does not leach. It is stored in seeds and fruit. It is most readily available to plants between a pH of 6 and 7.5 (unavailable in very acid or alkaline soils). It has a central role in energy transfer and protein metabolism. Phosphorus has also a role in fat, carbon, hydrogen, and oxygen metabolism, in respiration, and in photosynthesis. Found in greatest concentration in sites of new cell growth. Phosphorus absorption is reduced at low soil temperatures. Phosphorus is necessary to stimulate early root formation and growth, hasten crop maturity, stimulate flowering and seed production, give winter hardiness to fall plantings and seedings, and promote vigorous start (cell division) to plants.

Potassium (K): Potassium (potash - K_2O) is highly mobile in plants, and generally immobile in soil. It tends to leach. Potassium promotes vigour and disease resistance, helps development of root system, improves plant quality, and increases winter hardiness due to carbohydrate storage in roots. Increases protein production, and is essential to starch, sugar and oil formation and transfer and in water relations. It helps in osmotic and ionic regulation.

Calcium (Ca): Calcium is immobile in plants, and relatively immobile in soil. It is moderately leachable. Calcium is necessary for cell elongation and division, protein synthesis, root and leaf development, and plant vigour. It influences intake of other nutrients and increases calcium content of plants, important in cell wall structure and as an enzyme activator.

Magnesium (Mg): Magnesium is mobile in plants, mobile in acid soils, and fairly immobile above pH 6.5. It leaches from soil. Magnesium is necessary for formation of sugars, proteins, oils, and fats, regulates the uptake of other nutrients (especially P), is a component of chlorophyll, and is a phosphorus carrier.

Sulphur (S): Sulphur is mobile in plants, somewhat immobile in soil. Organic sulphur is converted into available sulphate sulphur by soil bacteria. It is also leachable. It is rarely deficient. Sulphur is necessary to maintain dark green colour, stimulate seed production, and promote root and general plant growth. It is part of proteins, amino acids, and vitamins, important in respiration.

Iron (Fe): Iron is immobile in plants and mobility decreases in soil with increasing pH. Iron is necessary for chlorophyll maintenance. It is an essential component of many hemo and nonhemo Fe enzymes and carriers, including cytochrome (respiratory electron carrier) and the ferrodoxins. The latter are involved in key metabolic functions such as N fixation, photosynthesis and electron transfer.

Zinc (Zn): Zinc is important for plant enzyme system function, seed production, and starch production. It needed for auxin synthesis.

Manganese (Mn): Manganese involved in oxygen evolving system of photosynthesis. It can substitute for magnesium in many of the phosphorylating and group transfer reactions. It influences auxin levels in plant. Manganese increases availability of Ca, Mg.

Copper (Cu): Copper is a constituent of enzyme systems. It is involved in photosynthesis and respiration and the formation of lignin. It has indirect effect on nodule formation.

Molybdenum (Mo): Molybdenum is needed for enzyme activity in the plant and for nitrogen fixation in legumes. It is an essential component of enzyme nitrate reductase in plant.

Boron (B): Primary functions of B in plants are related to cell wall formation and reproductive tissue. It is necessary for nodule formation in legumes. It is associated with translocation of sugars, starches, nitrogen and phosphorus.

Chloride (Cl): Chloride is required by the plant for leaf turgor and photosynthesis. It is associated with osmoregulation of plants growing on saline soil.

Nickel (Ni): Nickel is required by plants for proper seed germination and is beneficial for N metabolism in legumes and other plants in which ureides (compounds derived from urea) are important in metabolism. Ni is the metal component in urease, an enzyme that catalyzes the conversion of urea to ammonium.

Sources of mineral nutrient elements

Nutrient	Sources
C	Carbamate
N	Organic matter
P	Apatite
K	Mica, Feldsper
Ca	Dolomite, Apatite, Calcite, Gypsum
Mg	Dolomite, Muscovite, Biotite, Olivine
S	Pyrites, Gypsum, Organic Matter
Fe	Pyrites, Magnetites
B	Tourmline
Cu	Chalcopyrite, Olivine, Biotite
Mn	Magnetites, Olivine, Pyrolusite
Mo	Olivine
Zn	Olivine, Biotite
Cl	Apatite
Ni	Nickeliferous limonite, Pentlandite [$(Ni,Fe)_9S_8$]

Manures

Organic Manures are plant and animal wastes that are used as sources of plant nutrients. They release nutrients after their decomposition. Manures are the organic materials derived from animal, human and plant residues which contain plant nutrients in complex organic forms. Manures have low nutrient content per unit quantity and have longer residual effect besides improving soil physical properties compared to fertilizer with high nutrient content. Major sources of manures are:

1. Cattle shed wastes - dung, urine and slurry from biogas plants
2. Human habitation wastes - night soil, human urine, town refuse, sewage, sludge
3. Poultry litter, droppings of sheep and goat
4. Slaughter house wastes - bone meal, meat meal, blood meal, horn and hoof meal, Fish wastes
5. Byproducts of agro industries - oil cakes, bagasse and press mud, fruit and vegetable processing wastes etc.
6. Crop wastes - sugarcane trash, stubbles and other related material
7. Water hyacinth, weeds and tank silt, and
8. Green manure crops and green leaf manuring material

Manures can also be grouped into bulky organic manures and concentrated organic manures based on concentration of the nutrients.

Bulky organic manures

Bulky organic manures contain small percentage of nutrients and they are applied in large quantities. FYM, compost and green-manure are the most important and widely used bulky organic manures. Use of bulky organic manures has several advantages:

- They supply plant nutrients including micronutrients
- They improve soil physical properties like structure, water holding capacity etc.,
- They increase the availability of nutrients
- Carbon dioxide released during decomposition acts as a CO_2 fertilizer
- Plant parasitic nematodes and fungi are controlled to some extent by altering the balance of microorganisms in the soil.

1. Farmyard manure

FYM refers to the decomposed mixture of dung and urine of farm animals along with litter and left over material from roughages or fodder fed to the cattle. On an average well decomposed FYM contains 0.5 % N, 0.2 % P_2O_5 and 0.5 % K_2O.

Partially rotten FYM has to be applied three to four weeks before sowing while well rotten manure can be applied immediately before sowing. Generally 10 to 20 t/ha is applied, but more than 20 t/ha is applied to fodder grasses and vegetables. In such cases FYM should be applied at least 15 days in advance to avoid immobilization of nitrogen.

Vegetable crops like potato, tomato, sweet-potato, carrot, raddish, onion etc., respond well to the farmyard manure. The other responsive crops are sugarcane, rice, napier grass and orchard crops like oranges, banana, mango and plantation crop like coconut.

The entire amount of nutrients present in FYM is not available immediately. About 30% of nitrogen, 60 to 70 % of phosphorus and 70 % of potassium are available to the first crop.

2. Vermicompost

Vermicompost is the excreta of earthworms, which is rich in humus and nutrients. *Vermicomposting* is the process of turning organic debris into earthworm castings. The worm castings are very important to the fertility of the soil. The castings contain high amounts of nitrogen, potassium, phosphorus, calcium, and magnesium. The content of the earthworm castings, along with the natural tillage by the worms burrowing action, enhances the permeability of water in the soil.

Materials for preparation of Vermicompost

Any types of biodegradable wastes-

1. Crop residues
2. Weed biomass
3. Vegetable waste
4. Leaf litter
5. Hotel refuse
6. Waste from agro-industries
7. Biodegradable portion of urban and rural wastes

Advantages of vermicompost

- Vermicompost is rich in all essential plant nutrients.
- Provides excellent effect on overall plant growth, encourages the growth of new shoots / leaves and improves the quality and shelf life of the produce.
- Vermicompost is free flowing, easy to apply, handle and store and does not have bad odour.
- It improves soil structure, texture, aeration, and waterholding capacity and prevents soil erosion.
- Vermicompost is rich in beneficial micro flora such as a fixers, P- solubilizers, cellulose decomposing micro-flora etc in addition to improve soil environment.
- Vermicompost contains earthworm cocoons and increases the population and activity of earthworm in the soil.
- It prevents nutrient losses and increases the use efficiency of chemical fertilizers.
- Vermicompost is free from pathogens, toxic elements, weed seeds etc.
- It enhances the decomposition of organic matter in soil.
- It contains valuable vitamins, enzymes and hormones like auxins, gibberellins etc.

2. Sheep and Goat Manure

The droppings of sheep and goats contain higher nutrients than FYM and compost. On an average, the manure contains 3% N, 1% P_2O_5 and 2% K_2O. It is applied to the field in two ways. The sweeping of sheep or goat sheds are placed in pits for decomposition and it is applied later to the field. The nutrients present in the urine are wasted in this method. The second method is sheep penning, wherein sheep and goats are kept overnight in the field and urine and fecal matter added to the soil is incorporated to a shallow depth by working blade harrow or cultivator.

3. Poultry Manure

The excreta of birds ferment very quickly. If left exposed, 50 percent of its nitrogen is lost within 30 days. Poultry manure contains higher nitrogen and phosphorus compared to other bulky organic manures. The average nutrient content is 3.03% N, 2.63% P_2O_5 and 1.4 % K_2O.

4. Green Manuring

It is a practice of ploughing the green plant tissues grown in the field or adding green plants with tender twigs or leaves from outside and incorporating them into the soil for improving the physical structure as well as fertility of the soil. It can also be defined as a practice of ploughing or turning into the soil, undecomposed green plant tissues for the purpose of improving the soil fertility.

The objective of green manuring is to add an organic matter into the soil and thus, enrich it with 'N' which is most important and deficient nutrient.

There are two types of green manuring:

i. Green manuring *in-situ*:

When green manure crops are grown in the field itself either as a pure crop or as intercrop with the main crop and buried in the same field, it is known as Green manuring *in-situ*. E.g.: Sunhemp, Dhaincha, Pillipesara, Urd, Mung, Cowpea, Berseem, etc.

ii. Green leaf manuring:

It refers to turning into the soil green leaves and tender green twigs collected from shrubs and tress grown on bunds, waste lands and nearby forest area. e.g.: Glyricidia, wild Dhaincha, Karanj. Forest tree leaves are the main sources for green leaf manure. Plants growing in wastelands, field bunds etc., are another source of green leaf manure.

The important plant species useful for green leaf manure are neem, mahua, wild indigo, Glyricidia, Karanji *(Pongamia glabra)*, calotropis, avise *(Sesbania grandiflora)*, subabul.

Characteristics/desirable qualities of a good manuring:

1. Yield a large quantity of green material within a short period.
2. Be quick growing especially in the beginning, so as to suppress weeds.
3. Be succulent and have more leafy growth than woody growth, so that its decomposition will be rapid.
4. Preferably is a legume, so that atm. 'N' will be fixed.
5. Have deep and fibrous root system so that it will absorb nutrients from lower zone and add them to the surface soil and also improve soil structure.
6. Be able to grow even on poor soils.

Stage of green manuring: A green manuring crop may be turned in at the flowering stage or just before the flowering. The majority of the G.M. crops require 6 to 8 weeks after sowing at which there is maximum green matter production and most succulent.

Advantages of green manuring:

- **i)** It adds organic matter to the soil and simulates activity of soil micro-organisms.
- **ii)** It improves the structure of the soil thereby improving the WHC, decreasing run-off and erosion caused by rain.
- **iii)** The G.M. takes nutrients from lower layers of the soil and adds to the upper layer in which it is incorporated.
- **iv)** It is a leguminous crop, it fixes 'N' from the atmosphere and adds to the soil for being used by succeeding crop. Generally, about 2/3 of the N is derived from the atmosphere and the rest from the soil.
- **v)** It increases the availability of certain plant nutrients like P2O5, Ca, Mg and Fe.
- **vi)** Growing of green manure crops in the off season reduces weed proliferation and weed growth.
- **vii)** Green manuring helps in reclamation of alkaline soils. Root knot nematodes can be controlled by green manuring.
- **viii)** When green manures are turned into the soil and decompose, they provide nutrition for soil organisms, thus protecting and enhancing the soil's biological activity.
- **ix)** The root mass of a green manure crop loosens and aerates the soil, consequently improving the soil structure.
- **x)** The roots and top growth maintain or increase the organic matter content of the soil, which improves soil tilth.
- **xi)** Green manure crops reduce soil compaction. They lessen the impact of rainfall and vehicle traffic.

Disadvantages of green manuring:

- **i.** Under rain fed conditions, the germination and growth of succeeding crop may be affected due to depletion of moisture for the growth and decomposition of G.M.
- **ii.** G.M. crop inclusive of decomposition period occupies the field least 75-80 days which means a loss of one crop.
- **iii.** Incidence of pests and diseases may increases if the G.M. is not kept free from them.
- **iv.** Application of phosphatic fertilizers to G.M. crops helps to increase the yield, for rapid growth of *Rhizobia* and increase the 'P' availability to succeeding crop.

Concentrated organic manures:

Concentrated organic manures have higher nutrient content than bulky organic manure. The important concentrated organic manures are oilcakes, blood meal, fish manure etc. These are also known as organic nitrogen fertilizer. Before their organic nitrogen is used by the crops, it is converted through bacterial action into readily usable ammoniacal nitrogen and nitrate nitrogen. These organic fertilizers are, therefore, relatively slow acting, but they supply available nitrogen for a longer period.

1. Oil cakes

After oil is extracted from oilseeds, the remaining solid portion is dried as cake which can, be used as manure. The oil cakes are of two types:

- Edible oil cakes which can be safely fed to livestock; e.g.: Groundnut cake, Coconut cake etc., and
- Non edible oil cakes which are not fit for feeding livestock; e.g.: Castor cake, Neem cake, Mahua cake etc.,

Both edible and non-edible oil cakes can be used as manures. However, edible oil cakes are fed to cattle and non-edible oil cakes are used as manures especially for horticultural crops. Nutrients present in oil cakes, after mineralization, are made available to crops 7 to 10 days after application. Oilcakes need to be well powdered before application for even distribution and quicker decomposition.

The average nutrient content of different oil-cakes is presented in the following table.

Average nutrient content of oil cakes

Oil-cakes	**Nutrient content (%)**		
	N	**P2O5**	**K2O**
Non edible oil-cakes			
Castor cake	4.3	1.8	1.3
Cotton seed cake (undecorticated)	3.9	1.8	1.6
Karanj cake	3.9	0.9	1.2
Mahua cake	2.5	0.8	1.2
Safflower cake (undecorticated)	4.9	1.4	1.2
Edible oil-cakes			
Coconut cake	3.0	1.9	1.8
Cotton seed cake (decorticated)	6.4	2.9	2.2
Groundnut cake	7.3	1.5	1.3
Linseed cake	4.9	1.4	1.3
Niger cake	4.7	1.8	1.3
Rape seed cake	5.2	1.8	1.2
Safflower cake (decorticated)	7.9	2.2	1.9
Sesamum cake	6.2	2.0	1.2

2. Other Concentrated Organic Manures

Blood meal when dried and powdered can be used as manure. The meat of dead animals is dried and converted into meat meal which is a good source of nitrogen. Average nutrient content of animal based concentrated organic manures is given as follows.

Organic manures	**Nutrient content (%)**		
	N	**P2O5**	**K2O**
Blood meal	10 - 12	1 - 2	1.0
Meat meal	10.5	2.5	0.5
Fish meal	4 - 10	3 - 9	0.3 - 1.5
Horn and Hoof meal	13	-	-
Raw bone meal	3 - 4	20 - 25	-
Steamed bone meal	1 - 2	25 - 30	-

Fertilizer

A **fertilizer** is any material of natural or synthetic origin (other than liming materials) that is applied to soils or to plant tissues (usually leaves) to supply one or more plant nutrients essential to the growth of plants.

Organic Manures	Fertilizers
1. Nutrients from natural sources.	1. Nutrients from artificial sources.
2. Natural or organic origin	2. Mineral origin
3. Low nutrient compared to fertilizers.	3. High nutrient content
4. Very complex	4. Simple salts.
5. 30 days or more to decompose.	5. Soluble or give rapid response.
6. Organic nutrients contain all the nutrients.	6. Only specific nutrient.
7. Do not cause side effects	7. Cause side effects
8. Examples: Excrete of animals, animal matter (blood, bones, flesh, horn)	8. Examples: urea, DAP, MOP, Superphosphate.

Classification of Fertilizers:

1. Straight fertilizers: Straight fertilizers are those which supply only one primary plant nutrient, namely nitrogen or phosphorus or potassium.

eg. Urea, Ammonium sulphate, Potassium chloride and Potassium sulphate.

2. Complex fertilizers: Complex fertilizers contain two or three primary plant nutrients of which two primary nutrients are in chemical combination. These fertilisers are usually produced in granular form.

eg. Diammonium phosphate, Nitrophosphates and Ammonium phosphate.

3. **Mixed fertilizers**: are physical mixtures of straight fertilisers. They contain two or three primary plant nutrients. Mixed fertilisers are made by thoroughly mixing the ingredients either mechanically or manually.

Fertilisers can also be classified based on physical form: i.e., Solid and Liquid fertilizers

Solid fertilizers are in several forms *viz.*

i. Powder (single superphosphate),

ii. Crystals (ammonium sulphate),

iii. Prills (urea, diammonium phosphate, superphosphate),

iv. Granules,

v. Supergranules (urea supergranules) and

vi. Briquettes (urea briquettes).

Liquid fertilizers:

1. Liquid form fertilizers are applied with irrigation water or for direct application.

2. Ease of handling, less labour requirement and possibility of mixing with herbicides have made the liquid fertilisers more acceptable to farmers.

Based on the concentration of primary plant nutrient (N, P, K), fertilisers are classified into:

1. **High analysis fertilizer:** The total content of primary plant nutrient is more than 25%. e.g. Urea (46%N), Anhydrous ammonia (82%N), DAP (18:46), Ammonium Phosphate(20:20)
2. **Low analysis Fertiliser:** The total content of primary plant nutrient is less than 25%. e.g. SSP (16%P_2O_5), $NaNO_3$ (16%N)

Acidity and Basicity of Fertilizers:

Acid forming fertilizer: The fertilizer which leaves an acid residue is called an acid forming Fertilizer**.** It should be applied to alkaline soils. The amount of $CaCO_3$ required to neutralize the acid residue of an acid forming fertilizer is called Equivalent Acidity.

Fertilizer	Equivalent Acidity
Ammonium Nitrate	60
Urea	80
Ammonium Phosphate	86
Ammonium Sulphate Nitrate	93
Ammonium Sulphate	110
Ammonium Chloride	128

i.e., 100 kg of Ammonium Sulphate produces acidity for which 110 kg of $CaCO_3$ is required for its neutralization.

Alkaline forming/ Basic Fertilizers: The fertilizer which leaves an alkaline residue is called an alkaline forming Fertilizer**.** It should be applied to acid soils.

Fertilizer	Equivalent Basicity
Calcium Nitrate	21
Sodium Nitrate	29
Di-calcium Phosphate	25
Calcium Cyanamide	63

Nitrogenous Fertilizers:

Nitrogenous fertilizers take the foremost place among fertilizers since the deficiency of nitrogen in the soil is the foremost and crops respond to nitrogen better than to other nutrients. More than 80 per cent of the fertilizers used in this country are made up of nitrogenous fertilizers, particularly urea. It is extremely efficient in increasing the production of crops. This type of fertilizer is divided into different groups according to the manner in which the Nitrogen combines with other elements. These groups are Nitrate form, Ammonium form, Chemical compounds that contains both Nitrate and Ammonium form and Amide form.

Nitrate Fertilizer:

The Nitrogen is present in the form of Nitrate (NO^{-3}). This Nitrogen is highly mobile in soil and immediately available to plants. Hence it is usually suitable as top- and side-dressing. Due to its high solubility and mobility, it is subjected to leaching. In waterlogged soil, there is denitrification (microbial reduction of NO^{-3}). It increases alkalinity in soil, hence should be used for acidic soil.

1. **Sodium Nitrate: 15.6%** N
2. **Calcium nitrate [$Ca(NO_3)_2$]:** 15.5% N and 19.5% Ca. The NO3– is readily available, but the material is extremely hygroscopic.
3. **Potassium nitrate [KNO_3]:** N (13%) and K_2O (45%).

Ammoniacal Fertilizer:

Ammoniacal fertilizers contain the nitrogen in the form of ammonium. These fertilizers are readily soluble in water and therefore readily available to crops. Except rice, all crops absorb nitrogen in nitrate form. These fertilizers are resistant to leaching loss, as the ammonium ions get readily absorbed on the colloidal complex of the soil. Hence well suited to submerged soils. All Ammoniacal fertilisers are acidic. Hence used for basic/alkaline soils.

1. **Ammonium Sulphate** [$(NH_4)_2$ $S0_4$]: 20.6% ammoniacal N and 24% S
2. **Ammonium Chloride** (NH_4Cl): 26% ammoniacal N
3. **Ammonium phosphates**:
   a. Monoammonium phosphate (MAP) [$NH_4H_2PO_4$] : 11–13% N and 48–62% P_2O_5
   b. DAP: [$(NH_4)_2HPO_4$]: N- 18% and P_2O_5 46%
4. **Anhydrous ammonia** (NH_3): This fertilizer type is a colourless and pungent gas containing 80-82% of nitrogen. It is volatile in nature. Hence should be applied 10-20 cm deep in the soil.
5. Aqua Ammonia: It results from the absorption of Ammonia gas into water, in which it is soluble. It is used for preparation of other fertilisers.

Fertilizer containing N in both Nitrate & Ammoniacal Form:

1. **Ammonium Nitrate: (NH_4NO_3)**: contains 33 to 35% nitrogen, of which 50% is nitrate nitrogen and the other 50% in the ammonium form. This type of fertilizer can be explosive under certain conditions, and, should thus be handled with care.
3. **Calcium ammonium nitrate (CAN):** containing 26 per cent of N and 10% Ca. Half of its total N is in the ammoniacal form and half is in nitrate form.
4. **Ammonium Sulphate Nitrate [$(NH_4)_2SO_4$ NH_4NO_3]**: This fertilizer type is available as a mixture of ammonium nitrate and ammonium sulphate and is recognizable as a white crystal or as dirty-white granules. This fertilizer contains 26% N, 3/4 of it in the ammoniacal form and 1/4 (i.e. 6.5%) as nitrate nitrogen. In addition to nitrogen it contains 12.1% S.

Amide Fertilizer:

1. **Urea [$CO(NH_2)_2$]**

This is the most widely used fertilizer, available in a white, crystalline, organic form. It is produced by reacting NH3 with CO2 under pressure and high temperature. It is a highly concentrated nitrogenous fertilizer and is hygroscopic. It contains 46% N. Its high concentration of N brings about savings in storage, transportation, handling and application. Urea is also produced in granular or pellet forms and is coated with a non-hygroscopic inert material.

It is highly soluble in water and therefore, subject to rapid leaching. It is, however, quick-acting and produces quick results. When applied to the soil, its nitrogen is rapidly changed into ammonia. The application of Urea as fertilizer can be done at sowing time or as a top-dressing, but should not be allowed to come into contact with the seed.

2. **Calcium cyanamide** ($CaCN_2$)

- Calcium cyanamide contains 20.6 per cent of nitrogen.
- It is a greyish white powdery material that decomposed in moist soil giving rise to ammonia.

Phosphatic Fertilizer Types

Phosphatic fertilizers are chemical substances that contain the nutrient phosphorus in absorbable form (Phosphate anions). The nutrient phosphorus present in phosphate fertilizers are usually expressed in terms of phosphoric anhydride or simply as phosphorus pentaoxide (P_2O_5). The amount of phosphorus available to the plants depends upon the extent to which the fertilizer supplies HPO_4^{--} or $H_2PO_4^-$ ions.

According to the solubilities, the phosphatic fertilizers are divided in following groups.

a. **Water soluble phosphatic fertilizers**: **Superphosphates** [$Ca(H_2PO_4)_2$]. There are two types of superphosphates.

- Single superphosphate (SSP) with 16% and 12% S.
- Triple (or concentrated) superphosphate (TSP or CSP) with 44% P2O5 is made by acidulating rock phosphate with phosphoric acid, so it has only 1–1.5% S.

The common examples of these fertilizers are:

S.N.	Fertiliser	% P_2O_5
I	Single Superphosphate	16% P_2O_5
Ii	Double superphosphate	32% P_2O_5
Iii	Triple superphosphate	46 - 48% P_2O_5
Iv	Ammonium phosphate	20% P_2O_5

b. **Citric acid soluble phosphatic fertilizers**

Citric acid soluble phosphatic fertilizers are not soluble in water but are readily soluble in acidic water or weak acids like 2 per cent citric acid. They also contain phosphorus in available form, i.e., HPO_4. The fertilizers are suitable for acidic soils where they can easily dissolved and become available to plants. The citric soluble fertilizers are suitable for acidic soils because at low pH citrate soluble phosphorus is converted to monocalcium phosphate. Phosphorus is not fixed as iron and aluminium phosphate. The examples of these fertilziers are:

a) Basic slag -18% phosphate (P_2O_5): a by-product of iron and steel industries

b) Dicalcium phosphate -34-39% P_2O_5

c. **Water and citrate insoluble phosphatic fertilizers:** These mineral fertilizers contain phosphorus, which is insoluble in water as well as in citric acid. They are suitable in strongly acid soils or organic soils. The phosphorus is very slowly released by microbes at action and remains in soil for long time.

Rock Phosphate $Ca_3(PO_4)_2CaF_2$	: 20 - 30% P_2O_5
Bone meal $(Ca(PO_4)_2)_3 CaF_2$	: 21 - 25% P_2O_5

Potassium Fertilizer types

Chemical Potassium fertilizer should only be added when there is absolute certainty that there is a **Potassium deficiency** in the soil. Potassium fertilizers also work well in sandy garden soil that responds to their application. Crops such as chilies, potato and fruit trees all benefit from this type of fertilizer since it improves the quality and appearance of the produce. There are basically two different types of potassium fertilizers:

Muriate of Potash: It is a gray crystal type of fertilizer that consists of 60% potash. It should not be applied as top dressing as the chlorine content has harmful effect on the chlorophyll.

Sulphate of Potash: Sulphate of potash is a fertilizer type manufactured when potassium chloride is treated with magnesium sulphate. It dissolves readily in water and can be applied to the soil at any time up to sowing.

NUE is a critically important concept for evaluating crop production systems and can be greatly impacted by fertilizer management as well as soil- and plant-water relationships. NUE indicates the potential for nutrient losses to the environment from cropping systems as managers strive to meet the increasing societal demand for food, fiber and fuel. NUE measures are not measures of nutrient loss since nutrients can be retained in soil, and systems with relatively low NUE may not necessarily be harmful to the environment, while those with high NUE may not be harmless.

The efficiency is expressed in different ways such as the percent utilization of Nitrogen (**Apparent nitrogen recovery**), economic yield per unit of Nitrogen applied (**Agronomic efficiency**) or grain yield in relation to the nitrogen uptake (**Production efficiency**).

$$\text{Apparent nitrogen Recovery (ANR) (\%)} = \frac{\text{N uptake in the fertilized plot} - \text{N uptake in the control plot (kg/ha)}}{\text{Fertilizer N applied (kg/ha)}} \times 100$$

$$\begin{array}{l}\text{Agronomic Efficiency (AE)} \\ \text{(kg grain per kg Nitrogen applied)}\end{array} = \frac{\text{Grain yield in fertilized plot} - \text{Grain yield in control plot (kg/ha)}}{\text{Fertilizer N applied (kg/ha)}}$$

$$\begin{array}{l}\text{Production Efficiency (PE)} \\ \text{(kg grain per kg Nitrogen absorbed)}\end{array} = \frac{\text{Grain yield in fertilized plot} - \text{Grain yield in control plot (kg/ha)}}{\text{N uptake in the fertilized plot} - \text{N uptake in the control plot (kg/ha)}}$$

High nutrient uptake and less loss lead to high ANR. High AE is achieved if the incremental yield per unit of N applied is high. This is usually so when the N rates applied are low and the soil is low in N. High N in the grains as compared to the other plant parts leads to a higher PE. Under Indian conditions the use efficiency of nitrogenous fertilizers are only about 50% but under flooded or submerged condition in rice fields it is only about 28 – 34 % or about 30%.

Chapter 6

Water resources and soil – plant – water relationships

Sources of water for crop plants

Plants get their water supply from natural sources and through irrigation. Natural sources supply the largest part of water required by the crop plants in most of the places particularly under humid climate. However crop yields fluctuate widely when it is grown under rainfed condition due uncertainties in rainfall. Irrigation on the other hand involves high capital for its exploitation and supply to crop fields.

A. Natural sources:

i. Precipitation – Rain, snow, hail and sleet are received on earth from the atmosphere that constitutes the precipitation. Rain is the largest part of precipitation and also the most important source of water for crops. In humid and sub humid areas where rainfall is moderate, crops are grown depending on rainfall. In low rainfall areas low water requiring crops are grown. Where irrigation water is available it is used as a supplement for rain water for growing crops. In cold climates, snow contributes to soil water as it melts with rise in temperature. Hail and sleet are very minor sources that are limited to their places of occurrence.

ii. Atmospheric water other than precipitation – Atmospheric water constitutes of dew, fog, cloud and atmospheric humidity which serves as a very minor source of water for crop plants. High atmospheric humidity, fog, dew and cloud are quite effective in reducing evaporation from soil surface and transpiration from plants owing to reduction in atmospheric demand. They thus reduce the soil water use thereby making it available for a longer period for crop plants. They sometimes make growing of crops possible with scanty rainfall. Cereals and vegetables are extensively grown in North Bihar under unirrigated conditions where dew acts as a supplementary water source.

iii. Ground water – The free water found beneath the ground surface is referred to as ground water. When a hole is bored sufficiently deep into the soil, free water accumulates into the hole and the surface of the water in the hole is termed as water table. Water table is dynamic in nature and rises up during the rainy season due the recharge of the ground water by heavy rainfall. During the summer season the water table goes down due to evapotranspiration and subsurface flow. When the water table rises and comes near the crop root zone, a considerable amount of water is utilized by the crop plants. Besides due capillary movement water rises to some distance above the water table depending upon the soil texture. The capillary rise of water is more in finer soils like silt or clay compared to coarser soil like sandy soils.

iv. Flood water – Occurrence of flood is a common phenomenon during the rainy period in many parts of India. Though occurrence of flood causes havoc damage both to human beings and crops but while passing over the land it infiltrates into the soil and recharges the ground water.

B. Irrigation water sources:

i. Surface water – Rain and melting snow form streams, rivers and fill reservoirs, ponds and tanks. These form the sources of surface water. Surface water forms the largest source for irrigation purpose. Dams are constructed across the rivers and water is diverted to agricultural fields through canals and distributaries by gravity flow. Supply of water from dams across rivers and streams are often seasonal. Tanks, ponds and lakes store a limited quantity of water and provide irrigation mostly on seasonal basis.

ii. Ground water – it is another important source of irrigation water. Seepage water from canals, reservoirs and lakes, influent drainage from rivers and percolating flood water recharge the ground water. Dug wells are constructed and shallow, medium and deep tube wells are constructed to pump out the ground water for irrigation purpose.

Role of water in plants

1) Water is a constituent of protoplasm. It is a structural constituent of plant cell and it maintains the cell form through turgor pressure. When plenty of water is available, cells are turgid and plants retain their normal structural form. Water accounts for the largest part of the body weight of an actively growing plant and constitutes 85 to 90 percent of the body weight of young plants and 20 – 50 percent of mature plants.
2) Water is a source of two essential elements, oxygen and hydrogen required for synthesis of carbohydrates during photosynthesis.
3) Water serves as a solvent of substances and a medium in plants allowing metabolic reactions to occur.
4) Water acts as a solvent of plant nutrients and helps in the uptake of nutrients from soils. Plants also absorb nutrients through leaves from nutrient sprays. These nutrients are carried to different plant parts in soluble form for use.
5) Food manufactured in green parts is distributed to various parts of the plant in soluble form where water acts as a carrier of the food materials.
6) Transpiration is a vital process in plants and occurs at a potential rate as long as water is available in adequate amounts. When there is deficit of water the transpiration is reduced thereby affecting the growth and yield of the plants. Transpiration also helps in absorption of nutrients from the plants.
7) Water is essential in hydraulic process in the plant. It helps in the conversion of starch to sugar.
8) Water helps to maintain the turgidity of cell walls. Water helps in cell enlargement due to turgor pressure and cell division which ultimately increase the growth of plant.
9) Water is essential for the germination of seeds, growth of plant roots, and nutrition and multiplication of soil organism.
10) Water helps in the chemical, physical and biological reaction in soil.
11) Leaves get heated up with solar radiation. Plants dissipate heat by inceased transpiration. Water acts as a buffer against high or low temperature injury as it has high heat of vaporization and high specific heat.

Irrigation Definition:

Irrigation is artificial application of water to soil for the purpose of supplying the moisture essential for normal plant growth and development". It is supplementary to water available from rainfall & ground water. Irrigation is applied into the soil for the following purposes:

1. To add water to the soil for supplying moisture essential for normal plant growth and development.
2. To provide crop insurance against short duration droughts.
3. To leach or dilute excessive salts in the crop root zone, thereby providing a favourable environment in the soil profile for absorption of water and nutrients.
4. To soften tillage pans.
5. To cool the soil and atmosphere, thereby making more favourable microenvironment for plant growth

History of irrigation

Irrigation is an age old art. Civilizations grew up at locations where water was available. In North India the canal system is found by a network of perennial rivers which have their source in the snow clad Himalayan Mountains. During the whole winter season, the rivers carry enormous amount of water for feeding the canals. But in the South they are mainly rainfed and in off season particularly, no water is left in rivers to do irrigation in winter. So agriculture in southern India is solely dependent on monsoons or the water stored during the rainy season in the tanks.

Irrigation development in India

Medieval India

There is evidence that irrigation was practiced in India during Vedic periods. The concepts of storing river flows behind a dam, distribution of stored water through canals so as to ensure equity among farmers and adequate irrigation to the crops were well known and practiced even before 3000 B.C. Further, the remains of Indus Valley Civilization that flourished up to 1750 B.C also revealed the existence of the farm communities in the Indian sub-continent.

British period

Irrigation development under British rule began with the renovation, improvement and extension of the then existing works. However, as a result of the famine during 1876 – 1878, the country received serious setback in agricultural production. Consequently, the First Famine Commission was setup by the Government in 1880, which recommended for irrigation development in droughtprone areas.

The last two years of the 19 Century (1899 – 1900) again witnessed devastating famines. This led to the appointment of First Irrigation Commission in the year 1901 to ascertain the usefulness of irrigation against famines. Big spurt in irrigation development was thus, observed in the first quarter of 20th Century.

Pre Independent India

Large scale irrigation in India began in the third decade of the 19th century with the construction of Cauvery Delta System in South India. One of the major irrigation projects that came up during this period was Triveni in Champaran District of Bihar.

Irrigated area in India

The net cultivated area in India is 141.4 mha while the gross cropped area is 195.1 mha. The gross irrigated area in India 88.4 mha while the net irrigated area is 63.2 mha.

Irrigated area in different states

The status of net and gross irrigated area in different regions shows that North India has the highest irrigated area followed by Western India. The Eastern India has the least irrigated area.Uttar Pradesh has the highest gross irrigated area followed by Punjab, Madhya Pradesh, Rajasthan, Andhra Pradesh, Haryana, Bihar and Gujarat. However considering the net irrigated area to net cultivated area Punjab has the highest irrigated area followed by Haryana, U.P, Tamil Nadu, Bihar and Andhra Pradesh.

Irrigation by different sources

Among the different sources of irrigation tube wells and other wells accounts for the highest source of irrigated area (62%) followed by canals (26%), other sources (9%) and tanks (3%) in descending order. More than half of the area has been under irrigation through tube wells and dug wells. Tube wells may be deep medium and shallow. Uttar Pradesh, Madhya Pradesh, Andhra Pradesh, Punjab, Rajasthan and Haryana in descending order share the largest area irrigated by canals. Tube wells form an important source of water in Uttar Pradesh, Punjab, Bihar and Haryana.

There are three major sources of irrigation in India. They are

a) Canals
b) Wells and tube wells
c) Tanks

wells and tube wells are the major source of irrigation. Canals ranks second while tanks stand third. Tank irrigation is common in the eastern and southern states. With the introduction of diesel and electric pumps well and tube well irrigated areas have increased considerably. The canals in India are of two types –

1. Inundation canals - which are drawn directly from the river without making any kind of Dam at their head to regulate the flow of the river. Such canals are used for diverting the excess water from rivers at the time of flood. When the flood subsided the level of the river falls below the level of the canal and therefore the canal dries up.

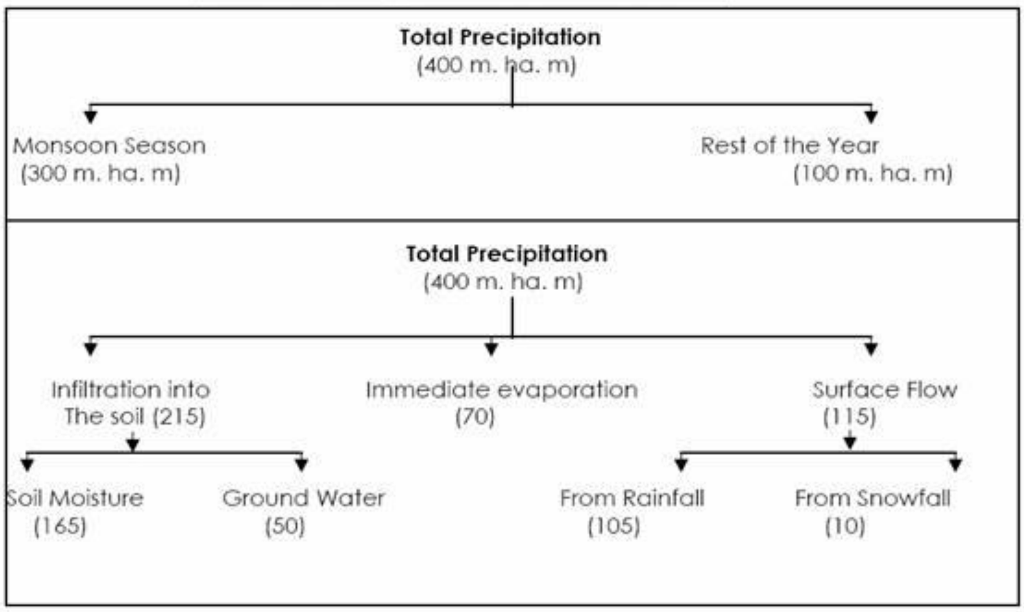
2. Perennial canals - canals which are constructed by putting some form of barrage across the river which flows throughout the year and divert the water by means of Canal to agricultural fields. Majority of the canals in India are of perennial type.

Water balance in India

India has a vast water wealth. The precipitation provides huge amount of water to fill tanks, lakes and reservoirs and a good flow of water through streams and rivers. The mean annual rainfall in the country is 1194 mm when considered over total geographical area of 328.7 mha, it makes available 392.5 mham of water. Thus India receives about 400 million hectare meters (mham) of rain and snowfall. Another 20 mham flow in as surface water from outside the country. This total 400 mhamof water goes to account for 70mhamwhich is lost as evaporation from the top thin layer of soil, 115 mham of runoff direct from rainfall and snow and 215 mham of water is infiltrated into the soil.

Out of 215 mham infiltrated water 165 mham remains as soil water and another 50mham is available as groundwater. The major part of annual precipitation infiltrates into the soil and contributes to ground water. The soil water constitutes of 172 mham of water which includes 165 mham of infiltrated rain water and 7 mham of water as contributed from ground water. The annual ground water recharge constitutes 50 mham from infiltrated rain water, 5 mham from infiltrated flood water and seepage from river and stream flows and 12 mham seepage from irrigation systems which makes the ground water wealth of about 67 mham. The country has asurface flows of 180mham of which 115 mham comes from runoff from rainfall and snow, 20 mham flows from outside the country and 45 mham from ground water flow. Out of 180 mham, 165 mham flows as river and stream and 15 mham is stored in reservoirs and tanks.

Flow chart showing the water resources of India



Rains in small amounts soak the top thin layer of surface soil and get evaporated quickly. This accounts for about 70 mham of evaporation from top thin soil layer. Another 65 mham of evaporation from soil water and 5 mham evaporation from the free water surfaces of tanks and reservoirs accounts for a total evaporation of 140 mham which is 35 percent of total precipitation in the country.

Transpiration by irrigated and unirrigated crops is estimated to be about 13 and 42 mham of water. Forests and other vegetation transpire upto 55 mham. This totals to 110 mham of water transpired by forests and other vegetation.

Water Resources of Bihar

Agriculture in Bihar is crucially dependent on monsoon. Although around 57 percent of its gross cultivated area is irrigated, irrigation itself is crucially dependent on monsoon as it largely depends on the use of surface water. According to the soil quality and climatic conditions of the relevant areas, Bihar has been classified in 3 agro-climatic zones : North-West Alluvial Plane (Zone1), North-East Alluvial Plane (Zone 2), and South Alluvial Plane (Zone 3), the last zone being further classified in two sub-zones 3A and 3B. Monsoon arrives earliest in the northeastern part (Zone2), which also receives the highest rainfall among all three zones. Zone 3 receives monsoon showers last of all three zones and also the least amount. Total irrigated area in the State is 45.67 lakh hectares, of which nearly 30 percent is fed by canal water. This highlights the monsoon dependence of even irrigated lands as catchment areas of nearly all the major rivers in the State are outside the state.

Soil water relationship

Soil water relations deal with those physical properties of soils and water that affectmovement, retention and absorption of water by plants and which must be considered inorder to plan or improve an irrigation system.

Soil – A three phase disperse system

Soil is a three phase system consisting of solid, liquid and gases. The mineral and organic matter in soil together constitute the solid phase which is the soil matrix, the liquidphase consists of soil water, which always contains dissolved substancesso that it shouldproperly be called the soil solution and the gaseous phase is the soil atmosphere. Mineral matter comprise the largest fraction of soil and exist in the form of particles of different sizes and shapes encompassing void spaces in soil called soil pore space. Organic matter is interspersed in soil minerals. The amount and geometry of soil pores depend on the relative proportions of different sizes and shapes of soil particles, their distribution and arrangement. The pore spaces remain filled with air and water in varying proportions, which are mainly manipulated by the amount of water present in the soil. The soil air is totally expelled out of soil when water is present in excess amount as in water logged soils.

Soil properties influencing soil-water relations

Soil depth

Soil depth refers to the thickness of soil cover over hard rock or hard substratum below which roots cannot penetrate. The soil depth is directly related to the development of root system, water storage capacity, nutrient supply and feasibility for land leveling and land shaping. Soil Conservation Division, Ministry of Agriculture, New Delhi, recognizes the following classes for irrigation purposes:

Soil depth classification

Soil depth	Class
Less than 7.5cm	Very shallow
7.5 – 22.5	Shallow
22.5 – 45.0	Moderately deep
45.0 – 90.0	Deep
More than 90	Very deep

A shallow soil has limited moisture holding capacity, restricted feed zone and root growth, therefore would need frequent irrigations with less water depth. Shallowness of soil is further unfavourable in areas needing land leveling and shaping because it affects soil-water relations besides nutrient retention & availability. Deep soil on the other hand, has good moisture holding capacity, larger feeding zone and good possibilities for development of root system. Soil depth is also important for interpreting water storage capacity.

Soil texture

Soil texture is the most important and fundamental property of the soil that is most intimately related to soil water relationship. It refers to the relative proportion of mineral particles of various sizes in a given soil i.e., the proportions of coarse, medium and fine particles, which are termed sand, silt and clay, respectively. Various combinations of these fractions are used to classify soil according to its texture. Using the name of the predominant size fraction designates texture. The relative sizes of sand, silt and clay as proposed by United States Department of Agriculture (USDA) and International Soil Science Society (ISSS) are:

Soil separates	Particle diameter (mm)	
	USDA	ISSS
Coarse sand	1.0 – 0.5	2.0 – 0.2
Fine sand	0.25 – 0.10	0.2 – 0.02
Silt	0.05 – 0.002	0.02 – 0.002
Clay	< 0.002	< 0.002

A sandy soil has greater proportions of large sized particles and is commonly termed as coarse or light soil. A clay soil has a high percentage of fine particles and is referred to as fine or heavy soils. A loam soil having almost equal amount of sand and clay is called as medium textured soil or medium soil.

The soil texture is closely related to:

1. Water holding capacity of the soil.
2. Quantity of water to be given at each irrigation i.e., irrigation water depth.
3. Irrigation interval and number of irrigations.
4. Permeability i.e., ability of the soil to transmit water & air.
5. Infiltration rate

For example, coarse textured soils (sandy soils) have low water holding capacity and facilitate rapid drainage and air movement. Therefore, crops grown on these soils require frequent irrigations with less irrigation water depth at each irrigation. On the other hand, fine textured soils (clayey) have relatively high water holding capacity, however the permeability for water and air is slow thus resulting in poor drainage and sometimes the soils get waterlogged. Considering its various effects, the soils with loamy texture are the ideal soils for growing most crops under irrigated conditions.

Soil structure

The structure of a soil refers to the arrangement of the soil particles and theadhesion of smaller particles to form large ones or aggregates. On the surface, soil structure is associated with the tilth of the soil.

The soil structure influences primarily:

1. Permeability for air and water
2. Total porosity and in turn water storage capacity in a given volume of soil
3. Root penetration and proliferation

Soils without definite structure may be single grain types, sands or massive type such as heavy clays. For example a structure-less soil allows water to percolate either too rapidly or too slowly. Platy structure restricts the downward movement of water. Crumbly, granular and prismatic structural types are most desirable for efficient irrigation water management and normal crop growth.

Physical properties of soil

Physical properties of soil play an important role in determining its suitability for economic crop production. Density of individual soil particles and of bulk is reported in relation to density of water, which is 1.0 g/cc. solid rock particles that go to form the soil normally weigh about 2650 kg/m^3. Weight of water being 1000 kg/m^3, specific gravity of soil is thus equal to 2650/1000 = 2.65.

Soil has solids, liquid and air and their relative masses and volume are often required for proper soil and crop management. The relationship may be expressed as:

$$Vt = Vs + Vw + Va$$

$$Mt = Ms + Mw + Ma$$

Where,

Vt = total soil volume
Vs = volume of soil solids
Vw = volume of soil water
Va = volume of soil air
Mt = total mass of soil
Ms = mass of soil solids
Mw = mass of soil water
Ma = mass of soil air (negligible)

Particle density: The particle density, also called is also called density of soil solids, is the ratio of mass of soil solids (Ms) of total volume of soil solids (Vs) and is expressed in g/cc or Mg/cc. density of soil solids or particle density of 2.6 g/cc means that its weight is 2.65 times that of water. In most mineral soils, the mean density of particles is about 2.6 to 2.7 g/cc. presence of soil organic matter lowers its value.

$$P.D = Ms/Vs$$

Dry Bulk density: A given bulk of soil is not all solid. On volume basis, it may contain about 50 percent pore space occupied by water and air. The dry bulk density or simply bulk density is the ratio of mass of oven dry soil solid particles (Ms) to the total volume of the soil (Vt). The volume includes the volume of soil solids (Vs), soil water (Vw) and soil air (Va). Bulk density is sometimes referred to as the apparent specific gravity. The difference between the two terms is that the bulk density is expressed as g/cc. while the apparent specific gravity is a dimensionless quantity.

$$B.D = Ms/Vt = Ms/ (Vs + Vw + Va)$$

Soil texture, structure, organic matter content and soil management practices influence bulk density of soil. In sandy soils the bulk density can be as high as 1.6 g/cc. in extremely compacted soils, bulk density might approach but never reach particle density. Ideal bulk density for optimum crop growth varies from 1.2 g/cc for a clay soil to about 1.4 g/cc for a sandy soil.

Total or wet Bulk density: It is the ratio of total mass of soil (Mt) to the total volume of soil (Vt).

$$\text{Wet } B.D = Mt/Vt = (Ms + Mw)/ (Vs + Vw + Va)$$

The wet bulk density depends more on the soil wetness or moisture content of soil.

Total Porosity: Soil pores are those parts of soil bulk not occupied by solid soil particles. In a field, soil pores are filled with water, air and other gases. Porosity (f) is the ratio of total volume of pore spaces (Vf) to the total volume of soil (Vt) and is expressed as a fraction or as percentage.

$$f = Vf/Vt = (Vw + Va)/ (Vs + Vw + Va)$$
$$= (Vt – Vs)/Vt = (1 – Vs/Vt) = 1 – (B.D/P.D)$$

Total porosity value generally lies in the range of 30 to 60% for arable soils. Coarse textured soils tend to be less porous (35 – 50%) than the fine textured soils (40 – 60%), though the mean size of individual pores is greater (>0.06mm in diameter) in the former than in the latter. Total porosity is inclusive of both, capillary (micro pores) and non-capillary porosity (i.e., macro pores). In a sandy soil, in spite of the relatively low total porosity, the movement of air and water is surprisingly rapid because of the dominance of the macro pores. Therefore the size of the individual pore spaces rather than their combined volume is an important consideration for optimum soil-water relations. For ideal conditions of aeration, permeability, drainage and water distribution, a soil should have about equal amount of macro and micro pore spaces. Knowledge of porosity in a given volume of soil is very important with respect to irrigation water management, because it is an index of moisture storage capacity and aeration conditions, the two most important factors that influence the plant growth and development.

Soil wetness: It refers to the relative water content of the soil and is expressed on weight basis or volume basis. Usually the soil water content is expressed on weight basis.

Mass wetness: Mass wetness is the ratio of mass of water to the mass of soil solids which is sometimes called gravimetric water content. It is expressed in percent.

$$\text{Mass wetness} = Mw/Ms*100$$

Volume wetness: It is the ratio of volume of water to the total volume of soil. It is also termed as volumetric water content. It expressed in percent.

$$\text{Volume wetness} = Vw/Vt*100$$

A relationship exists between mass wetness and volume wetness, which is given by

$$\text{Volume wetness} = \text{Mass wetness} \times \text{Apparent specific gravity}$$

Classification of Soil Water:

When water is added to dry soil either by rain or irrigation, it is distributed around the soil particles, where it is held by adhesion and cohesive forces. It displaces air in the pore spaces and eventually fills the pores. When all the pores, large and small are filled, soil is said to be saturated and it is at its maximum retentive capacity.

Although the soil water cannot be sharply demarcated, yet for sake of understanding and as per utility of water to plant it is mainly classified into following categories.

Soil water can mainly be classified into three heads:

- Gravitation water
- Capillary water
- Hygroscopic water

i) **Gravitational water:**when sufficient water is added to the soil, water gradually fills the pore system expelling the air completely from soil. A well drained soil cannot reach this stage of complete saturation as water starts moving downwards under gravity through the soil pores when the gravity exceeds soil water tension. The water in the macro pores are generally affected. This water is not available to the plants.

ii) **Capillary water:** With increasing supply of water, the water film held around the soil particles thickens. The water retained in the soil after the cessation of the downward movement is the capillary water. The soil water tension at this stage is 1/10 to 1/3 atm. Once this stage has reached the soil cannot hold any more water, and the excess water tends to move downwards under gravity. Capillary water is also known as water of cohesion. This water is held at a tension of 1/3 to 31 atm and much of it is in fluid state. Principal factors influencing the amount of capillary water in soils are the structure, texture, organic and colloidal matters present. A greater amount of water is held by a fine textured soil than coarse textured soil. The granular structure exhibits a higher capillary capacity. The more the organic and colloidal matter contents, the greater is the capillary capacity of soils.

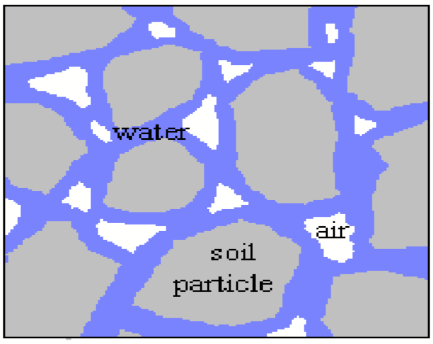
iii) **Hygroscopic water:** The water that an oven dry soil absorbs when exposed to air saturated with water vapour is termed as hygroscopic water. It occurs as a very thin film over the surface of soil particles and is held tenaciously at a tension of 31 atmospheres. Thus hygroscopic water represents the water held by soil in between 10,000 to 31 atmospheric tension. It is non-liquid and immobile at this stage. It is also termed as water of hydration or water of adhesion. This water is not available to plants.

Soil Moisture Constants

Field capacity

Field capacity denotes the water content retained by an initially saturated soil against the force of gravity. This stage is reached when the excess water from a saturated soil after irrigation or rainfall has fully percolated down. Field capacity presupposes the conditions that evaporation and transpiration are not active, downward movement of water has practically stopped and all the hydrostatic forces acting on soil water are in equilibrium. Soil water tension at field capacity ranges from 0.1 to 0.33 atm for different soils. It is 0.1 atm for sandy soils and 0.33 for clayey soils. However the value of 0.33 atm is commonly accepted. Field capacity is considered the highest limit of available water range. Soil water content at field capacity is usually higher in soils with higher content of silt and clay, organic matter and other colloidal matters.

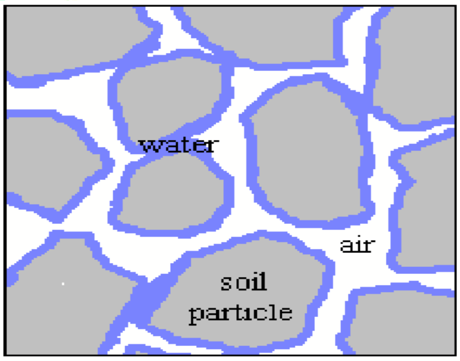
Figure 2.1 – Soil at field capacity Spaces between the soil particles filled with water and air



Permanent wilting point:

It refers to the water content of soil at which plants do not get enough water to meet the transpiration demand and wilt permanently. This stage of soil water is designated as permanent wilting percentage, wilting coefficient or permanent wilting point. Two stages of wilting point are recognized: 1.) temporary wilting point and 2.) Permanent wilting point. Temporary wilting point denotes the soil water content at which plants wilt during the day time but recovers during night or when kept in a humid chamber. Permanent wilting point represents the soil water content at which plants wilt permanently and fail to recover even when they are kept in humid chamber. Permanent wilting point is considered as the lowest limit of available water range as most of the plants do not get enough soil water for survival beyond this point. Sunflower is often used as an indicator plant in determining this point.

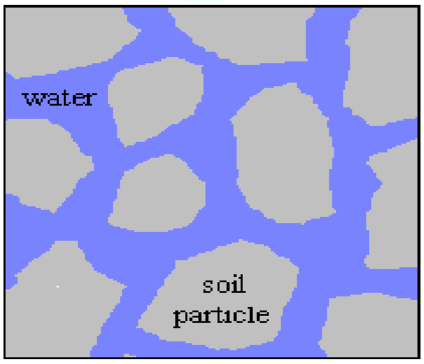
Figure 2.2– Soil at wilting point Spaces mostly filled with air, with a small amount of water held tightly around the soil particles



Saturation capacity

It is the water content of a fully saturated soil with all its pores completely filled with water under restricted drainage. It is also referred to as **maximum water holding capacity**. The soil water at this stage is in a free state and its tension is 0. The saturation capacity varies with soils. It increases with the presence of greater quantities of silt, clay, organic matter and colloidal matter. The water between field capacity and saturation is not available to the plants.

Fig 2.3. Saturated soil spaces between the soil particles totally filled with water



Hygroscopic coefficient: It is the maximum quantity of water absorbed by any soil in a saturated atmosphere (i.e. at 99 percent relative humidity) at 25 degree Celsius temperature. The hygroscopic coefficient varies with the type of soil, its texture and organic matter content. This constant is equal to a force of about 31 atmospheres and determined by placing the soil in a saturated atmosphere at 25^{o}C temperature. Water held by the soil at this constant is not available to plants because it is mostly in vapour form but it is useful to certain bacteria.

Available water

The water held by the soil between field capacity and wilting point and at a tension between 0.1 to 0.33 and 15 atm is available to the plants and is termed as available water. It consists of the greater part of the capillary water. Amount of available soil water depends on the texture, structure and the amount of organic matter and colloidal matter present therein. The granular structure and organic matter in soil increase the void space in soil resulting in greater storage and availability of soil water. The amount of water available within Field capacity and PWP is called the total available water (TAW) and the water available between half of F.C and PWP is called readily available water (RAW).

Unavailable water

There are two situations at which soil water is not available to most plants, i) when the soil water content falls below the Permanent wilting point and is held at tension of 15 atm and above and when the soil water is above Field capacity and is held at a tension between 0 and 1/3 atm. Gravitational water and hygroscopic water come under this class.

Energy concept of soil water

Soil water has energy in different quantities and forms. Out of two principal forms of energy i.e kinetic and potential energy, as the movement of soil water is very slow its kinetic energy is considered negligible. The potential energy which is the potential ability to do work results from the position of the water with regard to some reference point or level. Potential energy is very important in determining the state and movement of soil water. Movement of water between two points in a soil is caused by the difference in potential energy of water between two points. The natural tendency is that water moves from the region of higher potential energy to the region of lower potential energy to reach the equilibrium. Water molecules at the surface a body of water are considered to have no potential energy (zero potential) whereas the water held by a soil possesses negative potential. It is defined as the amount of work done by a unit quantity of water to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the point of soil water under consideration.

Forces acting on soil water

Soil water is constantly subjected to various forces that cause its retention by the soil matrix and movement through the soil medium. The forces acting on soil water are:

i) Matric forces
ii) Osmotic forces
iii) Gravitational forces

The matric and osmotic forces are negative forces and are known as matric tension and osmotic tension.

Matric forces

Matric forces consist of a group of forces that are (i) Adsorptive forces and (ii) Capillary forces.

Absorptive forces: Adsorptive forces cause water molecules adsorbed on clay particles in clay crystal lattices and around certain cations adsorbed on clay particles. A water molecule possesses an electrical charge and is a dipole. Clay particles in soil carry a negative charge and attract the water molecules that get adsorbed around the particles. The effectiveness of the attractive forces due to electrostatic field diminishes rapidly with distance from the clay particles.

Capillary forces: Capillary tension (negative force) is mainly responsible for retention of water around soil particles in the micro pores. When the water comes up from the soil below i.e from the water table below, the soil becomes moist for a considerable distance. This movement is due to capillarity and is similar to the rise of water in a capillary tube. Capillary forces comprise of two different forces, i) force of cohesion i.e liquid to liquid attraction and ii) force of adhesion i.e solid to liquid attraction.

i) Force of cohesion: The force of mutual attraction of water molecules in air – water interface is known as the cohesive force. The attraction of water molecules for each other is termed as surface tension. The surface tension is responsible for retention of water around soil particles as a very fine film.

ii) Force of adhesion: The other force involved in the capillarity is the adhesive force that acts in a solid – liquid interface. It represents the mutual attractive force between soil particles and water and is responsible for retention of water as a much thicker film.

Capillarity depends on both cohesive and adhesive forces. If the adhesive force is greater than the cohesive force the liquid will rise on the surface of the solid. If the adhesive force is greater than the cohesive force, the contact angle between the glass and water would be zero which is also considered same for water in soil.

The height to which water rises in a tube of capillary dimension depends on the surface tension and the weight of the water column. The weight of water column elevated to height h, is supported by the vertical component of surface tension acting around the perimeter of the tube.

Thus as the capillary tube gets finer the value of 'r' becomes smaller and this makes the water rise to a greater height. Thus in clay soils the water rises above the water table to a great height because of the smaller sized pore compared to sandy soils.

Osmotic force

Soil water contains some amount of dissolved salts and solutes and is termed as soil solution. Presence of solutes in water decreases the potential energy of water in it. Osmotic pressure is the property of aqueous solution. When aqueous solution is separated by a semi – permeable membrane from pure water or from a solution of lower concentration, water tends to diffuse or osmose into the concentrated solution through the membrane. The pressure that must be applied to prevent the diffusion of water is termed as osmotic pressure. Besides capillary tension, the osmotic tension is responsible for retention of water in soil.

Gravitational force

The gravity acts on soil water simultaneously with matric and osmotic tensions. As long as the gravity is lesser in magnitude than the matric and osmotic suctions (negative force) there is no downward movement of water. When the soil gets wet after rainfall or irrigation the combined effect of matric and osmotic suction decrease and become lower in magnitude than gravity. Thus the water has a downward movement. Downward movement ceases when the combined effect of matric and osmotic suctions are equal in magnitude to that of the gravity.

Soil moisture tension

The moisture held in the soil against gravity may be described in terms of moisture tension. Thus, soil moisture tension is a measure of the tenacity with which water is retained in the soil and reflects the force per unit area that must be exerted by plants to remove water from the soil. Several units have been used to express the force (energy) with which water is held in the soil. A common means of expressing tension is in terms of a **bar or atmosphere**. For instance, a pressure of one bar is approximately equal to the hydrostatic pressure exerted by a vertical column of water having a height of 1023 cm or a hydraulic head of 1023 cm. Again a pressure of 1 atmosphere is equivalent to the weight of 1036 cm of water column or 76.39 cm of mercury column over 1 square centimetre area. Similarly 1.0 bar is equivalent to 0.9869 atmospheres. The suction of water having a height of 10cm is equal to 0.01 bars or 10 millibars, that of a column of 100 cm high about 0.1 bar or 100millibars. Similarly 1.0 bar is equal to 100 centibars. Thus the higher the height of water column or bars or atmospheres the greater the tension or suction measured.

pF

In attempting to express the matric potential (or soil moisture tension) of soil water in terms of an equivalent hydraulic head (or energy per unit weight), it is understood that this head may be of the order of -100 cm or even -100000 cm of water. To avoid the use of such cumbersomely large numbers, Schofield (1935) suggested the use of pF (by analogy with the pH acidity scale), which is defined as the logarithm of the negative pressure (soil water tension or suction) head in cm of water. A tension of 10 cm of water is, thus, equal to a pF of 1. Likewise, a tension head of 1000 cm is equal to a pF of 3, and so forth. Approximate equivalents among expressions of soil water tension are given below in Table 2.1.

Table 2.1 Approximate equivalents among expressions of soil water tension

Soil moisture tension (bars)	Soil water potential (kPa)	Hydraulic head (cm)	pF value
-0.01	1	10.2	1.0
-0.1	10	102	2.0
-0.33	33	337	2.52
-1.0	102	1023	3.0
-15.0	1534	15345	4.2
-31.0	3171	31713	4.5

Soil water tension: It is the force per unit area that must be exerted to remove water from a non – saline soil at any water content. Tension or suction represents the negative force. Soil water tension is often referred to as soil water suction or matric suction. It measures the potential energy of water in soil with respect to free pure water. It presupposes that the soil is non – saline or the soil water exhibits a very negligible osmotic pressure.

Soil water stress: Soil water contains some amount of dissolved salts and thus exhibit some amount of osmotic tension. Salts and other solutes in soil water increase the force that must be exerted to extract water and influence the amount of water available to the plants. A saline soil has a stronger osmotic tension. The soil water tension together with the osmotic tension constitutes the soil water stress. In non – saline soils, soil water stress equals to soil water tension.

Total soil water potential

The total soil water potential is the sum of potentials resulting from different force fields. It may be defined as the amount of work done by unit quantity of water to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the point of soil water under consideration.

$$\psi_{soil} = \psi_g + \psi_{p(m)} + \psi_o$$

ψ_g= gravitational potential

$\psi_{p(m)}$ = pressure or matric potential

ψ_o= osmotic potential

Gravitational potential

Everybody on the earth's surface is attracted toward the earth's center by a gravitational force equal to the weight of the body, that weight being the product of the mass of the body and the gravitational acceleration. To raise a body against this attraction, work must be expended, and this work is stored by the raised body in the form of gravitational potential energy. It is evaluated at any point by the elevation of the point relative to some arbitrary reference level within the soil or below the soil profile in consideration so that the gravitational potential can always be taken as either positive or zero. Gravitational potential may be defined as the amount of work that a unit quantity of water in an equilibrium soil water system at an arbitrary level is capable of doing when it moves to another equilibrium identical in all respects, except that it is at a reference level. The gravitational potential is independent of the chemical and pressure conditions of soil water, and dependent only on relative elevation.

Matric potential

Matric potential is the negative pressure potential resulting from the capillary forces originating from the soil matrix. It is sometimes called the capillary potential or soil – water suction or matric suction. It results from the interactive capillary and adsorptive forces between water and the soil matrix, which in effect bind water in the soil and lower its potential energy below that of bulk water. The soil water in an unsaturated soil has no pressure potential, but has only matric potential.

Osmotic potential

While this phenomenon may not affect liquid flow in the soil significantly, it does come into play whenever a membrane or diffusion barrier is present that transmits water more readily than salts.The presence of solutes in soil water affects its thermodynamic properties and lowers its potential energy. The osmotic effect is important in the interaction between plant roots and soil, as well as in processes involving vapour diffusion.

Soil moisture characteristics curve

Soils differ considerably in their capacity to retain water. Soil characteristics such as texture and structure of soils, size and amount of pore space, amount and nature of organic colloidal matters and quantities of exchangeable cations present influence primarily the retention of water. The relative proportion of soil – water interfaces and the size and amount of pore space are most important in water retention. The soil moisture characteristic curve is strongly affected by soil texture. The greater the clay content, in general, the greater the water retention at any particular suction, and the more gradual the slope of the curve. In a sandy soil, most of the pores are relatively large, and once these large pores are emptied at a given suction, only a small amount of water remains. In a clay soil, the pore size distribution is more uniform, and more of the water is adsorbed, so that increasing the suction causes a more gradual decrease in water content. The soil moisture characteristic curves have marked practical significance. They illustrate retention-energy (suction) relationships, which influence various field processes, the two most important of which are the movement of water in soils and the uptake and utilization of water by plants. Thus help in scientific scheduling of irrigation's to field crops at optimum time and in proper quantity.

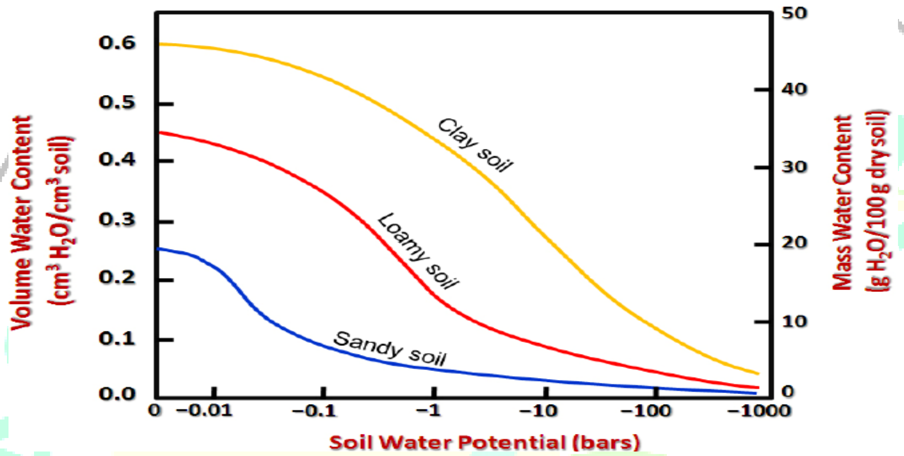


Figure 2.4 Soil moisture characteristic curves for soils varying in texture

Soil structure also affects the shape of the moisture characteristic curve, particularly at low suction range. Soil compaction decreases the total porosity, especially decreases the volume of large interaggregate pores. Hence, the saturation water content and initial decrease of water content at low suction is reduced. On the other hand, the volume of intermediate size pores is likely to be relatively greater in a compacted soil, while the interaggregate micropores remain unaffected. Hence, the curves for compacted and uncompacted soil may be nearly identical at high suction range. At very high suction range, water is held primarily by adsorption and hence retention is a textural than structural attribute.

Hysteresis

The moisture retention curve, i.e. the relationship between matric potential and water content can be obtained in two ways (i) by wetting a dry soil (sorption), (ii) by drying a saturated soil (desorption)

1. Sorption, by gradually wetting an initially dried soil, while reducing the suction.
2. Desorption by taking an initially saturated sample and increasing the suction to gradually dry the soil.

Each of these methods will give a continuous curve, but the two curves will not be identical. The soil moisture content at a given suction is greater in desorption than in sorption. This phenomenon is known as hysteresis. The hysteretic effect may be due to geometric non-uniformity of individual pores, entrapped air or swelling and shrinkage of the soil. Large pores which are bounded by smaller openings, will not empty until the pressure potential

(ψp)< 15/d, where d is the diameter of the small pores. However, these same pores will not fill until (ψp)> 15/d, where d is the diameter of the large pores. Therefore, the same moisture content can occur at two different tensions (pressure potentials) in the same soil (when the soil is being wetted and when the soil is being dried).

Movement of Water in Soil

Soil water is dynamic and moves constantly in the soil medium in different directions under different forces acting on it. Downward and lateral movements of water occur during and after irrigation or rainfall and upward movement takes place when upper soil layers start drying up owing to evaporation or evapotranspiration. Movements of water in soil may either occur in liquid or vapour form or both.

Infiltration

Infiltration is the process of entry of waterdownwards from the air medium, precisely the soil surface, into the soil medium. In irrigation practice it is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface is termed as infiltration. Infiltration rate or infiltrability is defined as the volume of water flowing into the profile per unit of soil surface area per unit time. Infiltration rate is very rapid at the start of irrigation or rain, but it decreases rapidly with the advance of time and eventually approaches a constant value. When water is applied it enters the soil as fast as it is supplied as long as the supply rate is less than the intake rate. When the supply rate exceeds the intake rate, water ponds over the area or moves down the slope as runoff.

$$i = Q/ (A \times T)$$

i = Infiltration rate (mm or cm/min or h)

Q = Volume quantity of water (m^3) infiltrating,

A = Area of the soil surface (m^2) exposed to infiltration, and

T = Time (min or h).

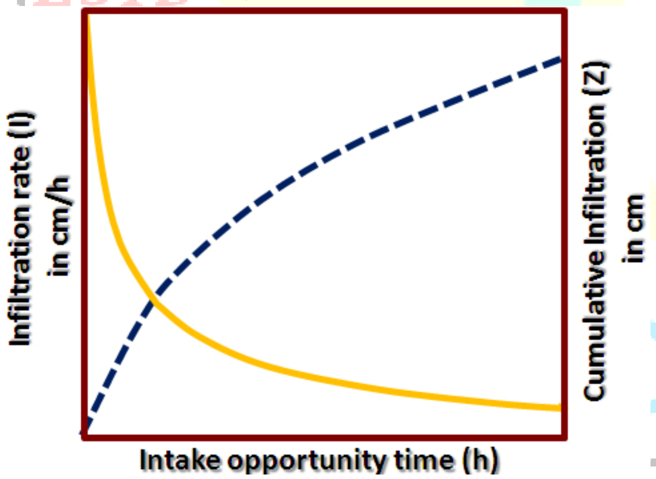


Figure. 2.5 Infiltration rate and cumulative infiltration

The infiltration rate is not constant over time. Generally, infiltration rate is high in the initial stages of infiltration process, particularly where the soil is quite dry, but tends to decrease monotonically and eventually to approach asymptotically a constant rate, which is often termed as basic intake rate or steady state infiltration rate. Whereas, the cumulative infiltration, being the time integral of the infiltration rate, has curvilinear time dependence, with a gradually decreasing slope. The infiltration rate of a soil may be easily measured using a simple device known as a Double Ring Infiltrometer. The variation of infiltration rate in different soil textures.

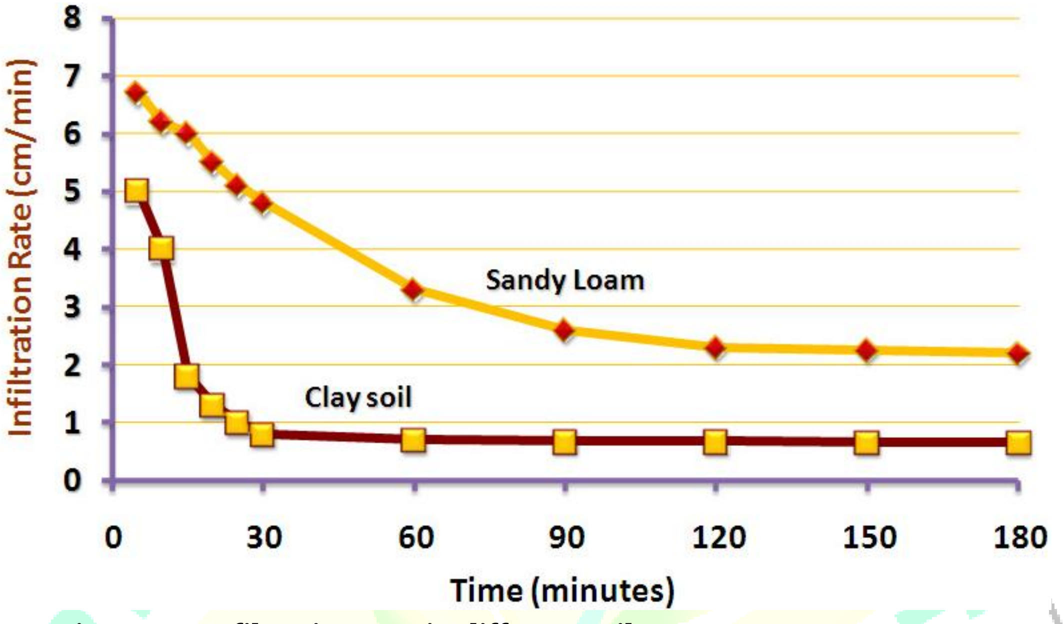


Figure 2.6 Infiltration rate in different soil type

Infiltration rate is grouped in to four categories

1. **Very Slow:** soils with less than 0.25 cm per hour e.g. - very clay soils.
2. **Slow**: infiltration rate of 0.25cm to 1.25 cm per hour e.g. Soils with high clay.
3. **Moderate:** infiltration rate of 1.25 to 2.5 cm per hour. e.g. - sandy loam/ silt loam soils.
4. **Rapid:** infiltration rate is more than 2.5cm per hour e.g. deep/sandy silt loam soils.

Factors affecting the rate of infiltration:

- **Compactness of soil surface:** A compact soil surface permits less infiltration whereas more infiltration occurs from loose soil surface.
- **Impact of rain drop:** the force (speed) with which the rain drop falls on the ground is said to be impact of rain drop. Ordinary size varies from 0.5 to 4mm in diameter. The speed of raindrop is 30ft per second and force is 14 times its own weight. When impact of raindrop is more then it causes sealing and closing of pores (capillaries) especially in easily dispensable soils resulting in infiltration rate
- **Soil cover:** Soil surface with vegetative cover has more infiltration rate than bare soil because sealing of capillary is not observed.
- **Soil Wetness:** If soil is wet, infiltration is less. In dry soil, infiltration is more.
- **Soil temperature:** Warm soil absorbs more water than cold soils.
- **Soil texture**: In coarse textured soils, infiltration rate is more as compared to heavy soils. In coarse textured soil, the numbers of macro-pores are more. In clayey soils, the cracking caused by drying also increases infiltration in the initial stages until the soil again swells and decreases infiltration.
- **Depth of soil:** Shallow soils permit less water to enter into soil than too deep soils.

A coarse surface textured, high water stable aggregates, more organic matter in the surface soil and greater number of micro pores, all help to increase infiltration. As it is a dynamic and quite variable character of soil, it can be controlled by management practices.

Cultivation practices that loosen the surface soil make it more receptive for infiltration e.g. course organic matter mulches increases infiltration.

Water intake time relationship

The relationship is important in order to decide the time to be allowed for application of a specified depth of water to a crop. A shorter period is allowed for infiltration in a soil with high intake rate compared to a soil with low intake rate. The stream size should be larger for soils with higher intake rate so that the irrigation water front advances at a faster rate and quickly covers the whole area.

Permeability

Permeability may be defined as the characteristics of a porous medium of its readiness to transmit a liquid. It is dependent on the pore size distribution in the soil. The larger the proportion of macro – pores, the greater is the permeability. Permeability usually decreases with depth as subsoil layers are more compact and have a usually small number of macro pores compared to the surface soil layers. The organic matter content, soil aggregates, texture, structure, colloidal matters, plough pan sodium concentration of water, tillage and crop management practices influence greatly the permeability of soil. Permeability decreases as the soil becomes drier following saturation.

Seepage

The lateral movement of water through soil pores or small cracks in the soil profile under unsaturated condition is known as seepage.

Water movement in saturated soil

Darcy's law

Experience shows that the discharge rate or flow rate Q (the volume V is flowing through the column per unit time) is directly proportional to the cross-sectional area and to the hydraulic head drop ΔH, and inversely proportional to the length of the column L:

$$Q \sim V/t \sim A\Delta H/L$$

The usual way to determine the hydraulic head drop across the system is to measure the head at the inflow boundary H_1 and at the outflow boundary H_0 relative to some reference level. Hydraulic head can be measured with help of Piezometer. In the following equation, ΔH is the difference between these two heads:

$$\Delta H = H_1 - H_0$$

Obviously, no flow occurs without a hydraulic head difference, that is, when $\Delta H = 0$. The head drop per unit distance in the direction of flow is in fact, the driving force. The specific discharge rate Q/A (i.e., the volume of water flowing through a unit cross-sectional area per unit time t) is called the flux density (or, simply, the flux) and is indicated by q. Thus, the flux is proportional to the hydraulic gradient:

$$q = Q/A = V/(A\times t) \sim \Delta H/L$$

The proportionality factor K is termed the hydraulic conductivity. It can be measured with the help of **Permeameters.**

$$q = K\Delta H/L$$

This equation is known as Darcy's law, after Henry Darcy. This equation gives an empirical relationship between water flux and energy gradient. Water flow in saturated soils is considered to follow Darcy's law.

The above equation can also be written as

$$Q = A\ K\Delta H/L$$

$$Q = A\ Ki$$

Where

i is the hydraulic gradient $i = \Delta H/L$, dimensionless

Hydraulic gradient is the head drop per unit distance in the direction of the flow. When the hydraulic gradient becomes unity that is the driving force is equal in magnitude to the force of gravity, then

$$V/t = K$$

i.e the velocity of flow (V/t) is equal to the hydraulic conductivity.

Limitations of Darcy's law

The law applies only when the flow is laminar. Laminar flow usually occurs in silt and clay soils. Hydraulic gradient more than unity may result in non- laminar flows in coarse sands, where Darcy's law cannot be applied. The usual index to find the tendency of flow to be laminar is the Reynold's number R_n, where Reynold's number less than unity indicates laminar flow.

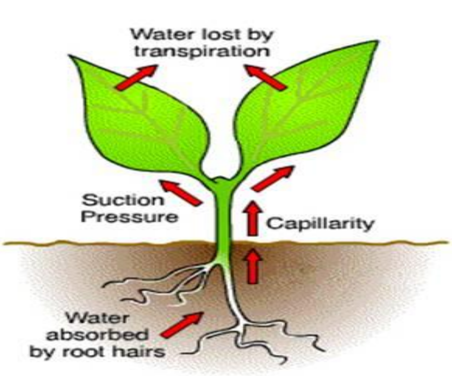
Hydraulic conductivity

It is the rate of flow of liquid through a porous medium under unit hydraulic gradient and is the proportionality factor K in Darcy's law. A soil with high porosity and large number of macro pores has high hydraulic conductivity.

Soil water – plant relationship

Plants that inhabit water saturated domains are called Hydrophytes or aquatic plants. Plants adapted to drawing water from shallow water tables are called Phreatophytes. In contrast, plants that can grow in arid regions by surviving long periods of thirst and then recovering quickly when water is supplied are called Xerophytes or desert plants. Some plants are specially adapted to growing in saline environment and are called Halophytes. Plants that grow best in moist but aerated soils generally in semi-humid to semiarid climates are called Mesophytes. Most crop plants belong to this category.

Plants grow on soil that provide them water and nutrients. They absorb the water from soils mainly through roots and use only 1.0 to 1.5 percent of the volume of water absorbed for building their vegetative structures and performing various biochemical and physiological activities. Soil, plant and ambient atmosphere taken together constitute a physically integrated dynamic system in which various flow processes occur independently like links in a chain which in a unified form is called soil plant atmosphere continuum (SPAC). In this system water flow always takes place from regions where its potential energy state's higher to where it is lower. The flow path includes liquid water movement in the soil towards the roots, liquid and perhaps vapour movement across the root to soil contact zone, absorption into the roots and across the membranes to the vascular tubes of the xylem, transfer through the xylem up the stem to the leaves, evaporation in the intercellular spaces within the leaves, vapour diffusion through the substomatal cavities and out of the stomata perforations into the air layer in direct contact with the leaf surface to the atmosphere.



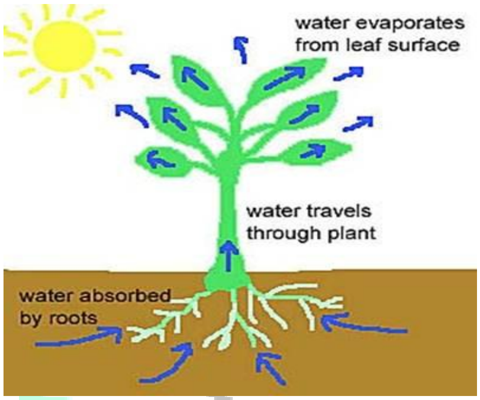


Fig. 2.7 Moisture absorption pattern by crops

Absorption of Moisture by Crops

Absorption of water is not dependent of process but it is related to transpiration. Absorption is controlled by rate of water loss in transpiration at least when water is readily available to the roots. Absorption and transpiration are linked by the continuous water column in xylem system of plants. Due to the loss of water in transpiration, it produces the energy gradient which causes the movement of water from soil in to the plants and from plants to atmosphere. In the maintenance of water column in xylem, the cohesive and adhesive properties of water play important role. Moisture enters in to plant roots by process of osmosis (movement of liquid through semi permeable membrane caused by unequal concentration on the two sides). The concentration of soluble material in cell sap of roots is increased because of loss of water through transpiration. When concentration of soluble material in cell sap within roots is greater than the soil moisture, the water passes in the roots to equalize the concentration. A more correct view to consider the concentration of water molecule in cell sap reduced because of quantity of soluble substances present and hence the number of water molecules in the soil solution is greater. As a result more water molecules strike against cell wall and water passes into the roots from the zone of higher concentration of water to a zone of lower concentration of water. When the concentration of soluble substances in the soil moisture exceeds that cell sap, situation will be reserved and water will pass out of the roots to the soil. Plants growing in saline soils with high concentration of soluble salts absorb water with difficulty due to high osmotic pressure of the soil solution.

The absorption of water by plants is closely related with transpiration. The sun provides energy for vaporization of water from leaves. Loss of water from leaf cells cause an increase in interior osmotic pressure which causes water to move in to them from xylem vessels. The xylem vessels of leaf are continuous with that of stem and roots and cause a tension created by loss of water from leaf to be transmitted to roots. Increased osmotic pressure in root cells occurs and uptake of water is encouraged. The absorption of water takes place in terminal portion of roots but the maximum absorption takes place in the zone of root hairs, 1 to 10 cm behind root tip. In other words, water is absorbed mainly through roots hairs. Root absorbs water both passively and actively. Passive absorption takes place when water is drawn into the roots by negative pressure in the conducting tissues created by transpiration. Under the conditions during which there is little transpiration, the roots of many plants absorb water by spending energy that is called active absorption. Under normal conditions of transpiration, the contribution of active absorption to the water supply of plant is negligible and it is usually less than 10 percent of total absorption. Certain plants are able to absorb moisture from the atmosphere when soil is at permanent wilting point. This is known as aerial absorption or negative transpiration. Direct absorption of water by leaves that are wetted by rain, dew or overhead irrigation can help to resaturate dehydrated leaf tissue. The leaves are borne through out the stem in all plants which are mainly responsible for the loss of water. The leaf surface shows small pores surrounded by two cells. The pores are called stoma and cells surrounding them are called guard cells. The stoma (stomata) regulates the loss of water as vapour and exchange of CO_2 in leaf and other organs. It is thus the efficiency of these structures which possibly determine water loss from plant. The efficiency of the stomata up on their size and number per unit area.

Energy concept of water absorption

Pure water has zero water potential, ψ. When solutes are present in water, the potential decreases below zero. A cell therefore has negative water potential. When a cell is placed in pure water, water moves into the cell due to gradient of decreasing ψ. This movement produces turgor pressure or pressure potential, ψ_p inside the cell and reduces the osmotic potential, ψ_s by diluting the concentration of the cell sap. The turgor pressure acts against the forces responsible for movement of water in the cell and is considered positive.

Cell = $\psi_s + \psi_m + \psi_p$

Where, ψ_{cell} = cell water potential

ψ_s = osmotic potential

ψ_m = matric potential

ψ_p= pressure potential

Value of ψ_s and ψ_m are negative while that of ψ_p is positive. The ψ_{cell} is usually negative, unless the cell is fully turgid. The cell water potential becomes zero when the cell becomes fully turgid. With the entry of water into the cell owing to the osmotic and matric potential, the pressure potential increases as the volume of the cell increases. The elasticity of the cell wall puts a limit to the increase in the cell volume.

A cell inside the plant system is surrounded by other cells while epidermal cells of the root are surrounded by soil water outside and the cortical cells inside. The gradient of decreasing water potential from epidermal cellsto xylem results in the radial movement of water in the roots.

Water movement in soil – plant – atmosphere system

When the soil – plant – atmosphere system is considered, difference in the magnitude of the water potential at different points in the system creates the driving force for the water to move from soil to the atmosphere through the plants. This movement occurs so long ψ_{air} is less than soil water potential ψ_{soil}.

Water when moves from soil through plants to the air takes the path along;

i) Epidermal cells in root
ii) Cortical cells and intercellular spaces in the cortex
iii) Conductive system of the xylem
iv) Leaf cells
v) Intercellular spaces in the leaf
vi) Stomatal cavities and stomata
vii) Air layer in the immediate vicinity of the leaf

In this system water takes the path of least resistance and moves as a continuous cohesive liquid from epidermal cells of root to the leaf cells. Water from leaf cells moves through the stomatal cavity to the air in vapour form. The evaporation from the leaves sets up imbibitional forces in leaf cell walls that are transmitted to epidermal cells of roots through the hydrodynamic system and causes the water absorption and then its ascent through the plant body.

Active absorption: A well-watered slowly transpiring plant absorbs water by active absorption under the tension developed in the root xylem due to matric effect of solid and the osmotic effects of the solutes present in it. This tension is also called the root pressure. Root pressure is only detectable during periods of low transpiration. The amount of water absorbed by active absorption is very negligible and is usually less than 5%of the total water required by a rapidly transpiring plant.

Passive absorption: In rapidly transpiring plant water loss from leaves exceeds the volume of water that the plant can absorb by active absorption. Thus a tension or diffusion pressure deficit is created in the mesophyll tissues of the leaves which is then transmitted through the hydrodynamic system into the xylem system in the roots and then to the root surface. Under conditions of rapid transpiration and high diffusion pressure deficit in the xylem system, water is literally pulled into the roots from the soil by mass flow. However, root tissues offer resistance to this movement and water absorption tends to lag behind the transpiration rate. The absorption lag causes development of water deficit and tension. Sometimes the water deficit is so high that plants show signs of wilting even when the water supply is adequate especially during summer mid days.

Factors affecting water absorption

1. **Atmospheric factors**: Evaporative demands of the atmosphere decides the rate of transpiration and consequently the rate of absorption. Temperature, relative humidity, winds and solar radiation are the principal atmospheric factors that decide the evaporative demand. High temperature, high wind, low relative humidity and greater solar radiation in combination cause transpiration at a higher rate thereby increasing absorption of water.
2. **Soil factors**: Available water, concentration of the soil solution, hydraulic conductivity of soil, soil temperature and soil aeration are the principal soil factors that affect the water absorption. In soils, where the hydraulic conductivity is high, movement of water towards roots occur faster resulting in greater availability of water to the plants. As long as the potential of the water is higher than plant water potential, the movement of water occurs towards plant.

   Concentration of soil solution in saline soils and arid soils remain high resulting in higher osmotic pressure of the soil solution. This reduces the gradient of water potential from soil to plant resulting in reduced absorption of water.

   Low soil temperature reduces the permeability of root cells and increases the viscosity of water causing reduction in water absorption. Again at low temperatures, root growth is restricted providing a smaller absorbing surface. Water absorption becomes significantly reduced at soil temperature below 20^0C and the reduction is more prominent in warm season crops. The amount of water absorption is linearly related to the temperature in the range of 10^0C to 25^0C. It declines beyond 25^0C. Temperatures beyond 40^0C in the rhizosphere often do not support water absorption and plants show symptoms of wilting.

Soil aeration becomes a problem in heavy soils particularly in high rainfall areas under poor drainage condition. Water logging causes poor aeration and interferes with the root growth and restricts water absorbing surfaces. As a result crops like maize, cowpea and mungbean show signs of wilting when the sun is bright after continuous rain.

3. **Plant factors**: Rate of transpiration, expanse of the root system and permeability characteristics of root cells are the principal plant factors that influence water absorption. Root growth, nature of the root system and distribution of the roots in the soil decides the volume of water available to the plants. A plant with deeper root system has access to a greater volume of water than a shallow rooted plant which can suffer from water stress even when the water is present in the deeper layers of the soil. New growth of roots is always desirable for better and greater absorption of water by the plants.

Water deficit and plant responses

Plants absorb water to do the normal function of nutrient absorption, transpiration and metabolic activities leading to growth and yield. When available soil water is not enough to meet the normal transpiration losses, a deficit in plant is created and under severe cases the growth ceases and finally death of plants occur.

Soil water deficit and plant stress condition:

The primary effect of water stress is the reduction of cell growth and cell wall synthesis. This is followed by changes in various biochemical processes such as reduction in carbohydrate assimilation, protein synthesis and nitrate reductase activity and accumulation of abscisic acid (ABA) and prolein. Water stress affects the growth and yield of plants in various ways such as root development, tiller formation, branching, flowering, seed formation and seed development are affected. Water stress causes reduction in internodal length of sugarcane, leaf area per plant in tobacco, incomplete filling of grains in cereals and fruit drop. Protein content of wheat grains and nicotine content of tobacco leaves increases with an increase in stress. Yields of vegetables and fodder in which succulent vegetative parts are wanted, are depressed considerably even by mild stress. Occurrence of stress in certain plant stages when the cell division and differentiation are significant, plants undergo some significant changes in their growth behaviour. A water deficit during crown root initiation stage in wheat, spike development stage in cereals and branching, flowering or seed development stages of crop plants is harmful and depresses the growth and yield significantly.

The field capacity and wilting point are generally considered as the uppermost and lower most limits of available soil water. The soil water within these two limits is termed as available soil water and the range of the available soil water between these two water constants is termed as available soil water range. It is also observed that yield declines drastically when the available soil water falls below a particular point within this range. This point is referred to as critical soil water tension for crop yield. Crops give optimum yield in most cases when the soil water is maintained from field capacity to 50% of available soil water and sometimes from field capacity to 25% of available soil water. The upper region of available soil water range provides the maximum amount of available water in the plants. It is usually within the soil water tension of one to two atmospheres that most of the available soil water is released.

Chapter 7

Crop water requirement and water use efficiency

Evapotranspiration

The crop water need (ET crop) is defined as the depth (or amount) of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally.

The crop water need always refers to a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and favourable soil conditions (including fertility and water). The crop thus reaches its full production potential under the given environment.

The crop water need mainly depends on:

- The climate: in a sunny and hot climate crops need more water per day than in a cloudy and cool climate
- The crop type: crops like maize or sugarcane need more water than crops like millet or sorghum
- The growth stage of the crop; fully grown crops reed more water than crops that have just been planted.

Evapotranspiration (ET = Evaporation + Transpiration)

Evaporation is a diffusive process by which water from natural surfaces, such as free water surface, bare soil, from live or dead vegetation foliage (intercepted water, dewfall, guttation etc) is lost in the form of vapour to the atmosphere. It is one of the basic components of hydrologic cycle. Likewise transpiration is a process by which water is lost in the form of vapour through plant surfaces, particularly leaves. In this process water is essentially absorbed by the plant roots due to water potential gradients and it moves upward through the stem and is ultimately lost into the atmosphere through numerous minute stomata in the plant leaves. It is basically an evaporation process.

Thus, evapotranspiration is a combined loss of water from the soil (evaporation) and plant (transpiration) surfaces to the atmosphere through vaporization of liquid water, and is expressed in depth per unit time (for example mm/day). Quantification of evapotranspiration is required in the context of many issues:

1. Management of water resources in agriculture.
2. Designing of irrigation projects on sound economic basis.
3. Fixing cropping patterns and working out the irrigation requirements of crops.
4. Scheduling of irritations.
5. Classifying regions climatologically for agriculture

Consumptive use

The term consumptive use (CU) is used to designate the sum of losses due to evaporation + transpiration from the cropped field as well as that water utilized by the plants in its metabolic activities for building up of the plant tissues. Since the water used in the actual metabolic processes is insignificant (about 1% of evapotranspiration losses) the term consumptive use is generally taken equivalent to evapotranspiration. It is expressed similar to ET as depth of water per unit time i.e., mm/day or cm/day.

a) Daily consumptive use: It is the total amount of the water used in ET plus water usedin metabolic activities by a crop during a single day or 24-hours period and is expressed in mm/day or cm/day.
b) Seasonal consumptive use: The total amount of water used by the crop in ET and metabolic activities for building up of plant tissues during its total growing season. It is essential to evaluate and decide the seasonal water supply to a command area of an irrigation project. It is important for planning the cropping pattern and cropping sequencein an area. It is expressed as surface depth of water in cm per hectare or hectare – cm.
c) Peak period consumptive use: The average daily water use rates in terms of ET plus that consumed in metabolic process during the highest consumptive use period (6 – 10 days) of the season is called peak period consumptive use rate. This is the design rate to be used in planning an irrigation system. The peak-use consumptive period generally occurs when the vegetation is abundant, temperature is high and crops are in flowering stage. The peak use rate for a shorter period of two to three days is higher than that for a longer period and is lower than the peak daily use rate. The peak use period is usually shorter in shallow soil and in soil with low water holding capacity. It is also shorter for crops with shallow root system.

Potential evapotranspiration

It refers to the highest rate of evapotranspiration by a short and actively growing crop or vegetation with abundant foliage completely shading the ground surface and abundant soil water supply under a given climate.

(The potential evapotranspiration concept was first introduced in the late 1940s and 50s by Penman and it is defined as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile". Note that in the definition of potential evapotranspiration, the evapotranspiration rate is not related to a specific crop. The main confusion with the potential evapotranspiration definition is that there are many types of horticultural and agronomic crops that fit into the description of short green crop.)

Reference crop evapotranspiration

Doorenbos and Pruitt (1975) used the term reference crop evapotranspiration. It refers to the rate of evapotranspiration from an extended surface of 8 – 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water.

ET_0 can be computed with any of the empirical formulae such as Blaney – Criddle, Modified Penman, Radiation and Pan evaporation methods for a month or a shorter period.

(Reference evapotranspiration is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m^{-1} (70 sec $3.2ft^{-1}$) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground". In the reference evapotranspiration definition, the grass is specifically defined as the reference crop and this crop is assumed to be free of water stress and diseases. In the literature, the terms "reference evapotranspiration" and "reference crop evapotranspiration" have been used

interchangeably and they both represent the same evapotranspiration rate from a short, green grass surface. Historically two main crops have been used as the reference crop, grass and alfalfa.)

Actual crop evapotranspiration

It refers to the rate of evapotranspiration by a particular crop in a given period under prevailing soil water and atmospheric conditions. The ET_{crop} varies under different soil water and atmospheric conditions and at different stages of crop growth, geographic locations and periods of the year.

$$ET_{crop} = Kc \times ET_0$$

Changes in the values of Evapotranspiration components during crop period

The two components of evapotranspiration are evaporation and transpiration. Transpiration loss accounts for the largest portion of ET. The evaporation occurring from the time of sowing to germination of the crop forms wholly the ET. After germination of the crop, transpiration becomes a constituent part of ET. Initially when the crop cover is insignificant, evaporation exceeds transpiration. As the crop grows there is development of vegetative cover shading the ground, transpiration rate goes on increasing with parallel decrease in evaporation rate. At this stage ET reaches its peak and further vegetative development does not bring any change in evapotranspiration. At maturity the transpiration and ET fall rapidly with simultaneous increase in evaporation.

Water Requirement

It is defined as the quantity of water regardless of its source, required by a crop or diversified pattern of crops in a given period of time for its normal growth & development under field conditions at a given place. In other words it is the total quantity of water required to mature an adequately irrigated crop. It is expressed in depth per unit time. Water requirement, if considered as a demand, it includes the quantity of water needed to meet the losses due to evapotranspiration (ET), plus the losses during the application of irrigation water (unavoidable losses) and the additional quantity of water required for special operations such as land preparation, transplanting, leaching of salts below the crop root zone, frost control etc.

$$WR = ET \text{ or } CU + \text{Application Losses} + \text{Special needs}$$

Water requirement of crops can also be expressed in terms of source of water-

$$WR = IR + EP + \Delta SW$$

When the water requirement is supplied entirely by irrigation, irrigation requirement and water requirement will be same.

Water requirement of crops

In crop fields, transpiration and evaporation go on simultaneously changing with time after rain or irrigation. Owing to the variable crop structures, root systems, nature of soils and soil conditions and energy status of water in plants and soil variable quantity of water escapes in to the atmosphere as evapotranspiration.

Water Requirement of Different Crops

Water requirement of crops refers to the amount of water required to raise a successful crop in a given period. It comprises thewater lost as evaporation from crop field, water transpired and metabolically used by crop plants, water lost during application which is economically unavoidable and the water used for special purpose such as land preparation, puddling of soil, salt leaching, retting of jute, harvesting of potato, ginger and groundnut and germinating seeds etc. It is usually expressed as the surface depth of water in mm or cm.

$$WR = ET + Wm + Wu + Ws$$

Where, WR – water requirement of a crop

E – Evaporation, T – Transpiration, Wm – Water used for metabolic activities by the plants, Wu – Unavoidable water loss during application, Ws – Water applied for special operations.

Amount of water required by a crop in its whole production period is called water requirement. The amount of water taken by crops vary considerably.

Crop	Water Requirement (mm)
Puddled Rice	1800-2000
Direct Seeded rice	1100 -1200
Wheat	350-400
Rabi Maize	400-450
Jowar	450-500
Barley	200-250
Chickpea	150-200
Lentil	120-180
Field Pea	200-250
Summer Greengram	250-300
Summer/Post Kharif Black Gram	270-330
Pigeonpea	210-280
Mustard	180-220
Linseed	250-310
Groundnut	400-450
Soybean	400-450
Sunflower	350-500
Sugarcane	1500-2500
Ragi	400-450
Potato	500-600
Onion	450-550
Berseem	500-700

Water required by the crops is essentially met from water sources such as rainfall, irrigation, soil water and ground water.

$$WR = P + I + \Delta SW + \Delta GW – (R+DP)$$

$$WR = EP + I + \Delta SW + \Delta GW$$

Where WR – water requirement

EP – effective precipitation

ΔSW – change in soil water storage

ΔGW – ground water contribution

I – Gross Irrigation requirement of the crop

Consumptive use or consumptive water use:

It is the sum of the volumes of water used by vegetation (crop) over a given area in producing plant tissue, in transpiration (T), plus that evaporated (E) from adjacent soil or from moisture intercepted on plant foliage. Since the volume of water used in producing plant tissue is negligible (<1%) compared with the volumes used in E and T, the CU can be taken to be approximately equal to ET.

Effective precipitation– The proportion of rainfall that is stored in the rhizosphere.

$$EP = P – (R+DP)$$

Where, EP = Effective precipitation

P – Precipitation

R – Runoff

DP – Deep percolation

Part of the rain may be lost as a surface run-off, deep percolation below the root zone of the crop or by evaporation of rain intercepted by foliage. When rainfall is of high intensity, only a portion of rainfall can enter the soil and stored in the root zone. In case of light rains of low intensity depending on the amount of moisture already present in the root zone of the crop, even the amount and intensity of rainfall, rate of consumption use, moisture storage capacity of soil, initial moisture content and infiltration rate of the soil. It is difficult to predict effective rainfall because of variation of soils, crops, topography and climate. However, in India it is assumed that 70% of the average seasonal rainfall to be effective in arid and semi-arid regions while 50% considered effective humid regions.

Irrigation requirement:

It is the total amount of water applied to a cropped field for supplementing effective rainfall, soil profile and groundwater contribution to meet the crop water requirements for optimum growth. In other words irrigation requirement is exclusive of ER + ΔSW + Gws

$$IR = WR – (EP + \Delta SW)$$

Net irrigation requirement (NIR):

It is the amount of water, exclusive of precipitation and profile soil moisture contribution, required for optimum crop production. In other words, it is the amount of irrigation water that must be stored in the root zone to meet the consumptive use requirement of a crop. In other words, it is the amount of irrigation water required to bring the soil moisture level in the effective root zone to field capacity. Thus it is the difference in depth or percentage soil moisture between field capacity and the soil moisture content in the root zone before starting irrigation.

$$NIR = \sum \frac{M_{2i} – M_{1i}}{100} \times A_i \times D_i$$

NIR = net amount of irrigation water to be applied at each irrigation

n = number of soil layers considered in root zone depth D

M_{1i} = soil moisture percentage at first sampling

M_{2i} = soil moisture percentage at second sampling

A_i = Apparent specific gravity of i^{th} soil layer

D_i = depth of i^{th} soil layer.

Gross irrigation requirement:(I) refers to the amount of water applied to the field from the start of land preparation to the harvest of the crops together with the water lost in conveyance through distributaries and field channels during irrigation to the crop field.

$$GIR = NIR / \text{Irrigation efficiency}$$

Seasonal irrigation requirement: It can be obtained by adding NRI values at each irrigation.

Irrigation efficiency

Irrigation efficiency is generally defined as the ratio of water output to the water input i.e. the ratio or percentage of the irrigation water consumed by the crop (Wc) to the water delivered to the field (Wf).

$$Ei = Wc/Wf \times 100$$

Irrigation efficiency indicates how efficiently the available irrigation water is used for crop production.

Factors influencing irrigation efficiencies

- Finer the soil texture higher the surface runoff and lesser the deep percolation losses compared with coarse sandy soils.
- Irregular land surface, compact and shallow soils reduce the irrigation efficiency.
- Irrigation efficiency will be low with small or too large irrigation streams.
- Long irrigation runs and excessive single applications contribute to large losses of irrigation water.

Types of irrigation efficiencies

1. **Reservoir Storage Efficiency:** It measures the fraction of storage utilised for irrigation. It also measures the volume of water lost or retained in the reservoir.

Es = Vol. of water delivered from the reservoir/ Vol. of water delivered to the reservoir for irrigation

2. **Water Conveyance efficiency**: Conveyance losses include direct evaporation or deep seepage in transit from source of supply to the point of supply. It is the ratio between water delivered to the irrigated plot and total quantity delivered from source. It is mathematically expressed as:

$$\mathbf{Ec} = Wf/Wd \times 100$$

Where:

Ec = Water conveyance efficiency (%)
Wf = Water delivered to the plot (l/sec)
Wd = Water delivered from the source (l/sec)

In irrigation distribution network i.e., distributaries, water courses, etc., the waterconveyance efficiency is used to find out what percentage of the released water at the head gate actually reaches the farm and is an indicator of the seepage losses in the conveyance losses. Thus a low Ec implies that much of the water released from the source is lost due to seepage in transit from source to the field.

3. **Water Application Efficiency:** Operational or delivery losses due to inefficient water handling during conveyance and losses on farm due to uneven distribution, poor handling, evaporation and deep percolation further reduces the efficiency of irrigation water. It is the ratio between quantity of water stored in the root zone and water delivered to the plot. It is mathematically expressed as:

$$\mathbf{Ea} = Ws/ Wf \times 100$$

Where:

Ea = Water application efficiency (%)
Ws = Water stored in the root zone (cm)
Wf = Water delivered to the plot (cm)

The concept of water application efficiency can be applied to a project, a farm or a field to evaluate the irrigation practices. All the factors, which influence the design of thesurface irrigation system therefore directly, affect the application efficiency. Thus a low Eaimplies that much of the applied water has been lost due to deep percolation or runoff.

4. **Water Distribution Efficiency:** Uneven surface distribution due to uneven land levelling, leaves some pockets unirrigated in the field, unless excess irrigation water is applied. This excess water lowers the irrigation efficiency.It is the ratio between the average numerical deviations in depth of water stored from average depth stored during irrigation (y) and the average depth stored during irrigation (d). It is mathematically expressed as:

$$\mathbf{Ed} = [1 - y/d] \times 100$$

Where:

y = Average numerical deviation in depth of water stored from average depth stored during irrigation
d = Average depth of water stored during irrigation

It is a measure of water distribution within the field. Low distribution efficiencymeans non-uniformity in the irrigation water penetration in the soil due to uneven landlevelling. The irrigation water cannot flow over the soil smoothly. There are low patcheswhere water will penetrate more and there are high patches where water cannot reach.This leaves some spots unirrigated unless excess irrigation water is applied. Excess waterapplication lowers irrigation efficiency.

5. **Water Storage Efficiency:** It indicates how efficiently the irrigation has met the crop needs. If only a fraction of the water needed is applied, Ea is 100 percent. Consequently, the storage efficiency (Es) is used to calculate how efficiently the soil – water deficit has been removed by the irrigation. When only a fraction of the needed water is being applied, the application efficiency is automatically 100%. Under such conditions, this will be a very poor irrigation practice since only a fraction of the water needed by the crop is added, although the application efficiency is 100%. Thus water storage efficiency is the ratio between water stored in the root zone (Ws) and the water needed (Wn) in the root zone prior to irrigation.

$$\mathbf{Es} = Ws/\ Wn \times 100$$

Where:

Es = Water storage efficiency (%)
Ws = Water stored in the root zone (cm)
Wn = Water needed in the root zone (cm)

The concept of water storage efficiency is useful in evaluating the irrigation methods especially under limited water supply conditions. It is also important when soils with low infiltration rates are to be irrigated. In such cases adequate time is to be allowed for the required amount of water to penetrate into the soil. This concept is also useful when salt balance of the root zone has to be taken into consideration and leaching requirement needs to be calculated. In such cases higher water storage efficiencies must be desirable to leach out the salts from the root zone. A low storage efficiency implies that water application is much less than actually needed. In a stretch of land one may get poor application efficiency for the upstream part and poor storage efficiency for the downstream section.

6. **Water Use Efficiency:** It is determined to evaluate the benefit of applied water through economic crop production. It is described in the following two ways:

i) *Field water use efficiency*: It is defined as the ratio of the amount of economic crop yield to the amount of water required for crop growing.

$$Eu = Y/WR$$

ii) *Crop water use efficiency*: It is defined as the ratio of the amount of economic crop yield to the amount of water consumptively used by the crop.

$$E_{CU} = Y/CU \text{ or } ET$$

7. **Project Efficiency:** It is the ratio between the average depth of water stored in the root zone during irrigation and water diverted from the reservoir. It is mathematically expressed as:

$$Ep = Ws/Wr \times 100$$

Where:

Ep = Project efficiency (%)
Ws = Water stored in the root zone (cm)
Wr = Water diverted from the reservoir (cm)

The overall irrigation efficiency of a farm is a product of:

$$Ef = Ea \times Es \times Ed$$

i.e. Ef = Water Application Efficiency × Water Storage Efficiency × Water Distribution Efficiency

The overall irrigation efficiency for a project (i.e., considering irrigation channels) is the product of $Ep = Ea \times Es \times Ed \times Ec$

Chapter 8

Scheduling of irrigation and methods of irrigation

Scheduling Irrigation

It is a means of supplying water in accordance with the crop needs. It a process of determining when to irrigate and how much water to apply.

Approaches for scheduling irrigation

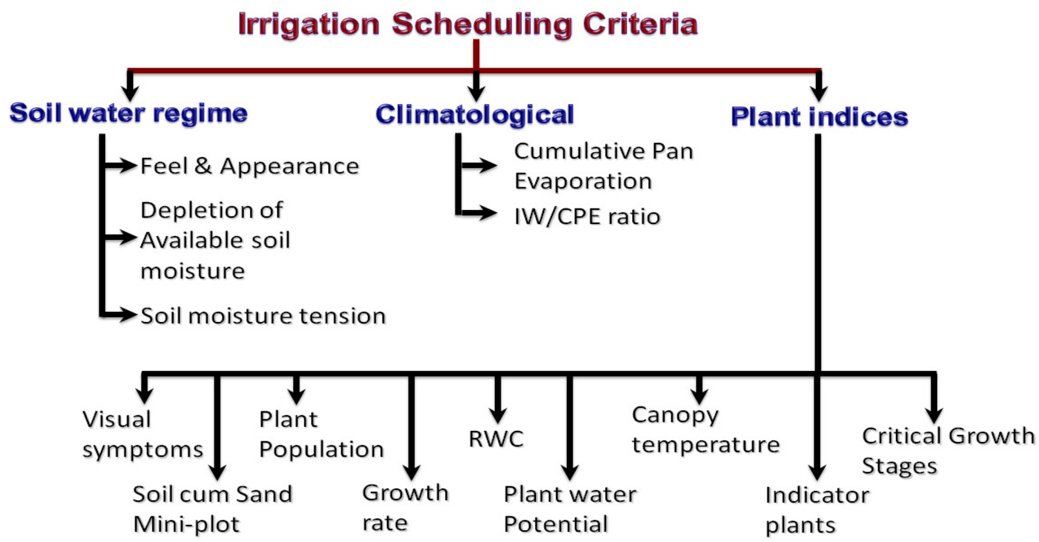
Crops differ in their tolerance to depletion of soil moisture. Crops such as rice respond to continuous land submergence or very high frequency irrigation. Some crops such as potato and most winter vegetables, require moist conditions (<40 to 50 DASM). Other crops such as small millets and fruit trees and several others with deep root system may show little reduction in yield until nearly all the available water has been depleted in the soil depth from which extraction has been most rapid. Irrigation scheduling decisions are to be made for mainly two situations:

1. Where water is expensive, irrigation should be scheduled to maximise crop production per unit of applied water.
2. Where good land is scarcer than water, irrigation should be scheduled to maximise crop production per unit of planted area.

Advantages of Irrigation Scheduling

Irrigation scheduling offers several advantages:

a) It enables the farmer to schedule water rotation among the various fields to minimize crop water stress and maximize yields.
b) It reduces the farmer's cost of water and labor through fewer irrigations, thereby making maximum use of soil moisture storage.
c) It lowers fertilizer costs by holding surface runoff and deep percolation (leaching) to a minimum.
d) It increases net returns by increasing crop yields and crop quality.
e) It minimizes water-logging problems by reducing the drainage requirements.
f) It assists in controlling root zone salinity problems through controlled leaching.
g) It results in additional returns by using the "saved" water to irrigate non-cash crops that otherwise would not be irrigated during water-short periods.



The different approaches include:

i. Soil moisture regime approach:

In these methods, soil moisture content is estimated to know the deficit available soil moisture at which it is proposed to irrigate based on predetermined soil moisture content to bring the soil to field capacity.

1) Soil water content approach: Irrigation scheduling on the basis of gravimetric soil – water content is based on two assumptions: assuming threshold moisture content below which the plant growth is adversely affected or determination of optimum fixed interval between two successive irrigations. Both these assumptions vary with soil texture. As, such, the soil water content approach may not be an ideal approach for irrigation scheduling.
2) Depletion of available soil water: This approach consists of determining the lower limit of available water in an assumed shallow root zone of the crops at which irrigation must be applied to avoid yield reduction. Soil moisture content is estimated by gravimetric sampling.
3) Soil water tension or soil moisture potential: Available water in soils at specific soil depths can be measured in terms of corresponding range of soil water potential or soil water tension by tensiometers/ irrometers or electrical resistance blocks for scheduling irrigation. Soil moisture tension approach is more useful for orchards and vegetable crop, particularly on coarse textured soils, where most of the ASM is held at low tensions. In soils with higher moisture holding capacity, properly calibrated gypsum blocks can be used for irrigation scheduling. One of the major drawbacks of this method is that this approach does not indicate the amount of irrigation to be applied directly but require soil moisture characteristic curve to interpret the soil moisture content.
4) Feel and appearance method:With experience, farmer can judge soil water content by the feel and also appearance of the soil. Soil samples are taken with a probe or soil auger from each quarter of the root zone depth, formed into a ball, tossed into air and caught in one hand. From the description given in Table 1, available moisture percentage is estimated for different textures of soils. Considerable experience and judgment are necessary to estimate available soil moisture content in the sample within reasonable accuracy.

Available soil moisture range	Coarse texture (loamy sand)	Moderately coarse texture (sandy loamy)	Medium texture (loamy and silt loamy)	Fine texture (clay loamy and silty clay loamy)
Field capacity (100%)	On squeezing, no free water appears on soil, but wet outline is left on hand	Similar symptoms		

75 to 100%	Tends to stick together slightly, sometimes forms a very weak ball under pressure	Forms weak ball, breaks easily, don't slick	Forms a ball, very pliable, slicks readily	Easily ribbons out between fingers, has slick feeling
50 to 75%	Appears to be dry don't form a ball with pressure	Tends to form a ball under pressure but seldom holds together	Forms a ball somewhat plastic, sometimes slick slightly with pressure	Forms a ball, ribbons out between thumb and fore-finger
25 to 50%	As above, but ball is formed by squeezing very firmly	Appears to be dry, don't form a ball unless squeezed very firmly	Somewhat crumbly but holds together with pressure	Somewhat pliable, forms a ball under pressure
0 to 25%	Dry, loose, single grained flows through fingers	Dry, loose, flows through fingers	Powdery dry, sometimes slightly crusted but easily broken down into powdery conditions.	Hard, baked, cracked, sometimes has loose crumbs on surface.

ii. Climatological approach

1) PET measurement: PET can be estimated from any of the empirical formulas and irrigation can be scheduled if the level of DASM in the root zone and evaporation during the crop period is known. PET can be estimated by several techniques viz., lysimetric methods, energy balance, aerodynamic approach, combination of energy balance and empirical formulae etc., and irrigation's can be scheduled conveniently based on the knowledge of PET or water use rates of crops over short time intervals of crop growth.
2) Cumulative pan evaporation: Earlier investigations have shown that transpiration of a crop is closely related to free water evaporation from an open pan evaporimeter. Thus, the open pan evaporimeter being simple and as they incorporate the effects of all climatic parameters into a single entity i.e., pan evaporation could be used as a guide for scheduling irrigation's to crops. For example,
    i) Wheat required 75 to 100 mm CPE at Ludhiana
    ii) Sugarcane required 75 mm CPE in Maharashtra
    iii) Greengram required 180 mm CPE at Ludhiana
    iv) Sunflower required 60 mm CPE at Bangalore
3) IW/CPE approach: Pan Evaporation (E_{pan}) can be used for scheduling irrigations. Prihar*et al* (1974) suggested relatively practical approach of IW/CPE as the basis for scheduling irrigation. An IW/CPE ration of 1.0 indicates scheduling irrigation with quantity of water equal to that lost in evaporation. If 5.0 cm of irrigation water is applied when the cumulative pan evaporation is 10 cm, the ratio will be 0.5 (5/10). This approach has been evaluated extensively to develop optimum irrigation schedules for different crops and agro climatic regions of the country.

iii. Plant indicator approaches:

Any physical measurement related directly or indirectly to plant water deficits and which responds readily to integrated influence of soil – water – plant factors and evaporative demand of the atmosphere may serve as a criterion for timing of irrigation to crops.

1) Visual plant symptoms: Symptoms of plant wilting such as drooping, curling and rolling of leaves in maize are visual indicators of plant needs for water. Change in foliage colour and leaf angle is used as indicator to irrigate beans. Water stress in some crops lead to appearance of carotenoid and anthocyanin pigments, shortening of internodes in sugarcane and cotton, retardation of stem elongation in grapes lack of new growth in terminal growth points of almond can be used as indices for scheduling irrigation to crops. Although this approach is simple and rapid, it suffers from many drawbacks like error in judgement, poor wilting of certain crops under moderate to severe stress and growth reduction in some crops even before the plant is visibly wilted. Adoption of this approach is constrained by inadequate standardization of techniques, nonavailability and high cost of equipment, selection of suitable growth parameters, lack of precision in growth measurements and variation of growth - water relationship with stages.

2) Plant water content or plant water potential: Plant water content is generally indexed from measurements of relative leaf water content and leaf water potential. Values of these parameters at any time of the day depend upon the time lag between evaporative demand of the atmosphere and uptake rate by the crop. As these values fall below certain critical limits, specific to plant species and their growth stages, the important physiological and growth phenomenon are adversely affected. Relative water content is the actual water content of the leaf or plant when sampled relative to the water at saturation or turgid.

RWC = (fresh weight - dry weight)/ (turgid weight - dry weight)

3) Plant and Canopy temperature: Leaf or canopy temperature is a sensitive index to plant water status. Canopy temperature at 1400 hrs is a better index of plant water status than that recorded at other times of the day. It is believed that difference between canopy temperature and air temperature is a better criterion of water stress than plant temperature alone. Jackson *et al* (1977) suggested the use of Stress Degree Day Index computed as ∑(canopy temperature – midday air temperature) for a period for determination of timings and amount of irrigation.

4) Critical crop growth stages: As a result of extensive experimentation, critical growth stages (moisture sensitive stages) of various crops for water demand have been identified. If irrigation water is scarce, irrigation are to be scheduled at least at these critical growth stages for maximum water use efficiency

Crops	Critical Stages
Rice	Initial tillering, flowering
Wheat	Most critical stage: Crown root initiation, tillering, jointing,. booting, flowering, milk and dough stages
Wheat	Boot stage; dough stage
Pulses	Flowering and podding.
Peas	Pre bloom stage.
Berseem	After each cutting.
Gram	Pre flowering and flowering.
Pigeonpea	Flower initiation, pod filling.
Sorghum	Initial seedling, pre flowering, flowering, grain formation.
Barley	Boot stage, dough stage
Maize	Early vegetative, taselling and silking stage.

5) Soil cum mini plot technique: In this method, 1x1x1 m size of pit is dug in the middle of the field. About 5% of sand (by volume) is added to the pit, mixed well with soil and the pit is filled up in natural order. Crops are grown normally in all areas including pit area. The plants in the pit show wilting symptoms earlier than the other areas. Irrigation is scheduled as soon as wilting symptoms appear on the plants in the pit.
6) Sowing high seed rate:In an elevated area, one square metre plot is selected and crop is grown with four times thicker than the normal seed rate. Because of high plant density, plants show wilting symptoms earlier than in the rest of the crop area indicating the need of scheduling of irrigation.
7) Indicator plants: there are few references about use of indicator plants as a guide for scheduling irrigation. In wheat scheduling irrigation on the basis of wilting symptoms in maize and sunflower gave the highest grain yields.

Comparison of the above irrigation approaches leads to the conclusion that an estimation of permissible soil moisture depletion is essential before the crop yield starts declining. Among the approaches, the IW/CPE ratio method appears to be ideal because of its simplicity when the water supply is adequate. When irrigation water is inadequate, irrigation may be scheduled at critical growth stages or at variable IW/CPE ratios. However the emphasis should lie on optimum yield with high water use efficiency rather than potential yield.

Methods of irrigation , surface, sprinkler and drip irrigation

Applications of irrigation water to cropped field by different types of layouts are called as irrigation methods. The methods of irrigation initially might have been started to check the over flow of water from one field to another. But today, it has become necessary to save the water by proper methods to arrest run-off loss, percolation loss, evaporation loss etc., and to optimize the crop water need. Hence, irrigation method can be defined as the way in which the water is applied to the cropped field without much application and other losses, with an objective of applying water effectively to facilitate better environment for crop growth.

Classification of Irrigation Methods

The irrigation methods are broadly classified as:

1. Surface method or gravity method of irrigation

A. Complete flooding of soil surface

i)Wild flooding ii) Border or border strip (a. Straight border b. Contour border)
iii)Check or check basin(a. rectangular check b. contour check)
iv) Contour ditch /contour channel irrigation

B. Partial flooding of soil surface

i) Furrow irrigation (a. Straight level furrow b. Straight graded furrow c. Contour furrow d. Alternate furrow e. Raised bed furrow f. Corrugation g Basin or ring irrigation)

C. Surge irrigation

2. Sub surface or sub irrigation

i) Irrigation by lateral supply trenches **ii**) Irrigation by underground pipe or tiles

3. Pressurized or micro irrigation - Drip irrigation, sprinkler irrigation and rain gun irrigation.

I. Surface or gravity irrigation

It is the common method of irrigation practiced all over the world. In this method, water is applied directly to the surface by providing some checks to the water flow:

Advantages

• Easy to maintain
• Low cost
• Technical skill is not required.

Prerequisites

• Uniform soil
• Smoothness of field surface or levelled surface
• Adequate quantity of water.

Classification

1. **Border strip method -** The field is divided into number of long parallel strips by providing small parallel earthen bunds or levees or dykes along both sides of the strips. The end along the strip may or may not be closed, which is based on the length of the strips. If the length of the strip is very long, the end will be closed to have a uniform distribution and to avoid run off loss. Each strip is irrigated independently from upper end (turned on) and water flow as thin sheet and uniformly spread along the strips. The water is turned off when the required volume is delivered to the strip. The application efficiency of this system is 75–85%.
Crop - All closely spaced crops like pulses, wheat, barley, alfalfa, berseem, grasses, ragi, and small grains.

2. Check basin method (beds and channel) - It is the common and simple method of irrigation mainly adopted in levelled land surface. It is also known as Beds and channel method of irrigation. The land is divided into small basins/beds. The area of basin is surrounded by earthen bunds or levees or dykes. The applied water is kept within the basin and not allowed for run off. This is the most common method adopted for most of the crops.

The size of the levees or ridges or bunds depends upon the depth of water to be impounded in the basin. The water is turned on the upper side and after applying the required quantity of water it is turned off.

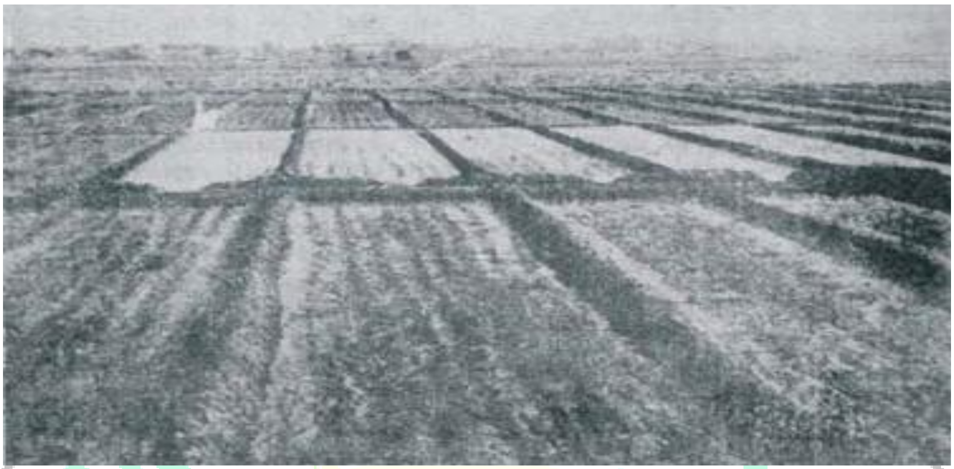


Fig. 5.1 Check basin method of irrigation

Crops - Cereals, millets, pulses, oilseeds.

3. **Basin method -** Basin method of irrigation is used in soil submergence method of irrigation in low land rice, bunded rainfed rice and forage grasses, where water is stagnated to the required depth by providing bunds on all the sides to sufficient width and height. The optimum size for efficient water management to rice crop is 0.25-0.40 ha. The field is to be levelled thoroughly for uniform depth of water. Provision of separate irrigation and drainage channels is more efficient than field-to-field irrigation.

4. Ring basin - This method is mostly adopted for wide spaced orchard crops. The rings are circular basins formed around the individual trees. The rings between trees are interlinked with main lead channel by sub channels to get water to the individual rings. As water is allowed in rings only, wastage of water spreading the whole interspaces of trees as in the usual flooding irrigation method is reduced. Weed growth in the interspaces around the rings are discouraged. This method ensures sufficient moisture in the root zone and saves lot of irrigation water.

Fig 5.2 Ring basin

B. Partial flooding of soil surface

1. Furrow method of irrigation - It is the common method adopted for row planted crops like cotton, maize, sugarcane, potato, beetroot, onion, sorghum, vegetable crops etc. In this method, small evenly spaced shallow furrows or channels are formed in the beds. Another method of furrow irrigation is forming alternate ridges and furrows to regulate water. The water is turned at the high end and conveyed through smaller channels. Water applied in furrows infiltrate slowly into the soil and spread laterally to wet the area between furrows.

2. Straight furrow - Best suited to soils where land slope does not exceed 0.75%.

3. Contour furrow - This method is similar to graded and level furrow method. Furrow carries water across slopping field rather than downwards. They are designed to fit the topography of field. Furrows are given a gentle slope along its length as in graded furrow. Field supply channels run down the land slope to feed the contour furrow and are provided with erosion control structure. Successfully used in all irrigable soils. All row crops including grains, vegetables and cash crops are adapted to this method. Light soil can be irrigated successfully across slopes up to 5% slope. Up to 8-10% can be irrigated by contour furrow. Contour furrow may be used on all types of soil except in light sandy soil and soil that crack.

4. Corrugation irrigation - It consists of running water in small furrows, which direct the flow down the slope commonly used for irrigation in non-cultivated close growing crops such as small grains, pasture on steep slopes. Corrugation can be made with a simple bamboo corrugation or cultivators equipped with small furrows. Corrugations are 'V' or 'U' shaped channels about 6-10 cm deep spaced 40-75 cm apart. This method is not recommended for saline soil or for saline water irrigation. The permissible length of corrugation varies from 15 cm within light textured soil with slopes of 2-4% to about 150 cm in heavy texture soil up to 2% slope.

5. Surge irrigation - Surge irrigation is a method of surface irrigation through furrows or border strips wherein water is applied intermittently in a series of relatively short on and off time periods during the irrigation (Humphrey, 1989). Water is let into a long furrows or border strips in an intermittent flow instead of conventional continuous flow. Each flow is termed as a surge.

Surge irrigation practiced under favourable conditions can improve the performance of surface irrigation system compared to the other methods of surface irrigation. Irrigation is given in an on-off cycle or by cut back method. The cycle time means the time from the beginning of one surge to the beginning of next surge. Cycle ratio is the ratio of flow time (continue) to the cycle time. Assuming the cycle time as 20 minutes and cycle ratio as 1:2 (0.5), the on-time is 10 minutes and off time is 10 minutes. This cycle ratio can also be the ratio of on-time and off-time as 1:1, if the on time is 10 minutes. Water is allowed for 10 minutes and stopped for 10 minutes. This 20 minutes is the surge time or cycle time. This surge is repeated until the water reaches the whole furrow or strip.

Fig. 5.3 Contour irrigation

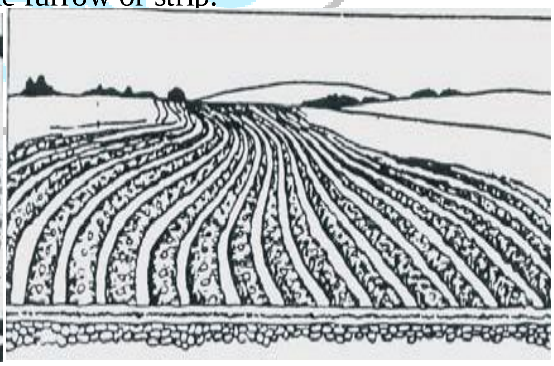


Fig. 5.4 Graded contour-furrow Irrigation

Fig. 5.5 Corrugated irrigation

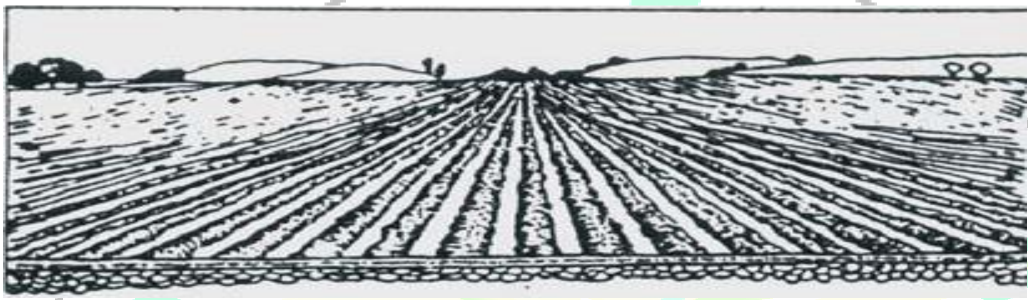


Fig. 5.6 Graded or level-furrow irrigation: Different types of furrow irrigation

II. Subsurface irrigation

Water is applied below the ground surface through the network of pipes or some devices. The main aim of this type of irrigation is to reduce the evaporation loss and to maintain an artificial water table near the root zone of the crop.

Suitability - It is mainly suitable for the high temperature area where ET losses are very high wherein controlling and maintenance of surface water and application is very difficult.

Pitcher pot irrigation method - It is one way of applying water below the ground or soil surface. In this method, in a mud pot, some small holes are made and the holes are closed by either threads or material, which is able to conduct water very quickly. The pots are kept around the root zone in pits made for it. The pits are completely covered tightly with sand mulch mix. The pots are filled with water and closed. The water slowly penetrates to root zone through the holes and wet the root zone area. This method is mostly suitable for widely spaced tree crops under water scarce conditions.

III. Pressurized irrigation methods (Micro irrigation)

It includes both sprinkler and drip irrigation methods where water is applied through network of pipelines by means of pressure devices.

1. **Sprinkler irrigation system/point source method -** In this method the irrigation water is sprayed to the air and allowed to fall on-the ground surface more or less resembling rainfall. The sprinkling of water or spray of water is made by pumping water under pressure through network of pipelines and allowing to eject out by means of small orifices or nozzles or holes. The water required by the crop is applied in the form of spray by using some devices, wherein the water application rate should be somewhat lesser than the soil infiltration rate to avoid run off or stagnation of water in the field.

Suitability and advantages

• It is highly suitable for sandy soil where infiltration rate is more.
• For shallow soil where levelling operation is technically not possible.

• For lands having undulating topography or steep slopes where levelling is economically not advisable.
• Irrigation steam size is very small where surface flow is low.
• It is almost suitable for all crops except crops like rice, which needs stagnation of water, but under water scarcity it can be tried for rice also. Reproductive phase in cotton sprinkler irrigation is not advisable.
• Application of fertilizer (fertigation), pesticides (pestigation) and herbicides (herbigation) are possible through irrigation systems which reduce labour cost and increase the use efficiency of any chemical.
• It controls crop canopy temperature.
• In crust soil, it facilitates early germination and establishment by means of light and frequent irrigation.
• Wastage of land for basin, ridges and furrows and irrigation channels are reduced.

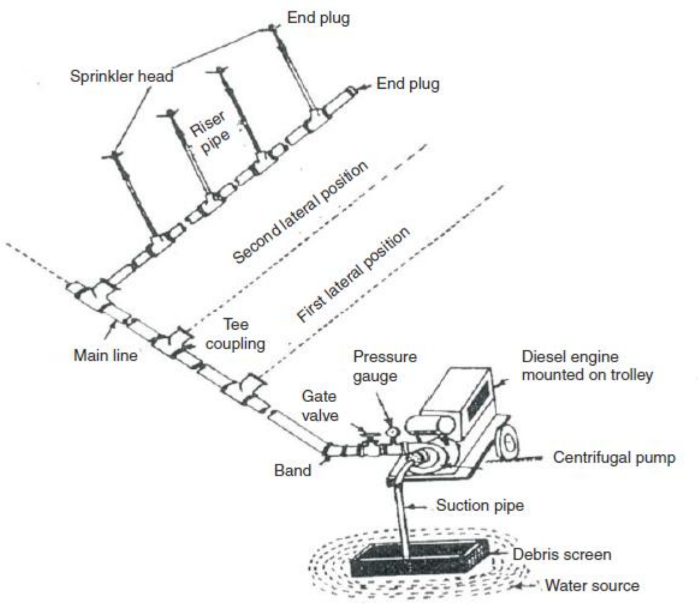


Fig. 5.7 Components of a sprinkler irrigation system.

Disadvantages
In heavy windy areas the distribution efficiency is reduced due to drifting of water droplets. In saline water conditions, it causes leaf burns besides clogging and corrosion of the pipeline. Continuous power supply is required to operate the system to maintain pressure. It is very costly to install and to maintain. Uniformity of application is difficult due to over application or neglected corners in the field.

Major components
• Pump set
• Network of pipelines (main, lateral, sub lateral, etc.)
• Riser pipes with tripod stand
• Sprinkler head

Classification - There are two types *viz.*, (1) Rotation head system and (2) Perforated pipe system.

(*a*) **Rotating head system -** A special device to sprinkle the water called “Sprinkler Head” is used in this system. The sprinkler head consists of small nozzles and metal ring or vane with a spring. The water ejected through the nozzle strike the metal ring which changes its direction by the help of the spring attached to this which in turn causes the spray of water in all directions. The whole sprinkler head system is fitted on the riser pipe, which is erected from lateral pipes at uniform intervals. Rotating sprinkler heads are of two types *viz.*, single nozzle type and twin nozzle type (main nozzle and driving nozzle).

(*b*) **Perforated pipes system -** In this method, small holes are made in lateral pipes based on the nature of the crops to distribute water uniformly.

Uniform distribution of water - Irrigation efficiency of sprinklers depends upon the degree of uniformity of water applied. Uniformity coefficient is computed with field application. Open cans are placed at regular interval within sprinkled area. Depth of water collected in open cans is measured and the coefficient of uniformity is computed by Christiansen (1942) equation.

$$Cu = 100(1-\Sigma X/m.n)$$

Where,

Cu = uniformity coefficient

m = average value of all observations

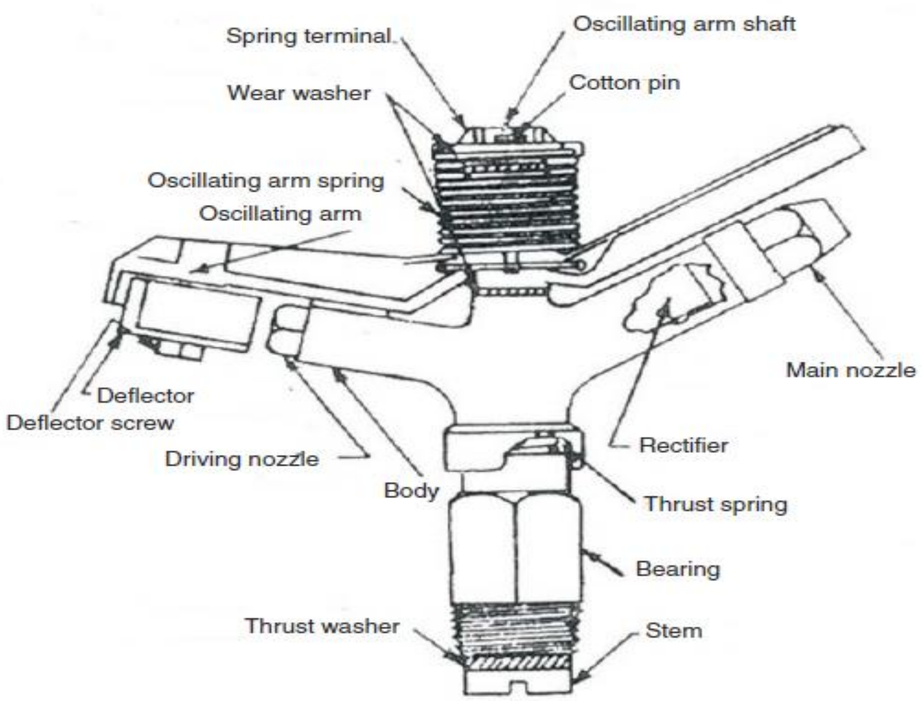
n = total number of observation points

X = numerical deviation of individual

observation from average application rate.

A uniformity coefficient of 85% or more is considered to be satisfactory. The uniformity coefficient is affected by pressure–nozzle size relation, sprinkler spacing and wind condition.

Sprinkler selection and spacing - The choice depends on diameter of coverage required, pressure available and discharge of sprinkler. The data given in tables 1 and 2 may serve as guidance in selecting the pressure and spacing desired.



2. Drip or Trickle Irrigation System/line source irrigation

Water is applied through network of pipelines and allowed to fall drop by drop at crop root zone by a special device called emitters or drippers. These drippers or emitters control the quantity of water to bedropped out. In this system, the main principle is to apply the water at crop root zone based on the daily

ET demand of the crop without anystress. Hence, the root zone is always maintained at field capacity level.

Components

• Overhead tank or pressure system (Motor pumps).

• Main Lines - To take water from source to field which is usually made of black poly alkathene pipes having an inner diameter of 50 mm

Sub main - If the area is larger, the sub mains are used to take water from main pipes to field which is normally having an inner diameter of 37 mm.

Laterals - These pipelines are normally having lesser diameter than mains and sub mains usually of 12 mm made of black poly alkathene pipes which deliver water from main or sub mains to crop root zone. The length of lateral depends upon the pressure created in pump as well as spacing of the crop and length of the field. Normally about 25 m length of lateral can be adopted to have a uniform distribution of water.

Emitters - Emitters control the water drops and the quantity of water to be delivered. Various designs of drippers with various discharge capacity are available (5, 7, 8, 10 and 20 lph, etc. Button types, spray type, tap type etc.). Instead of drippers micro tubes are inserted into the laterals and water is allowed to drip in the root zone of crops or trees.

Advantages

• Application of water in slow rates facilitates the easy infiltration into the soil.

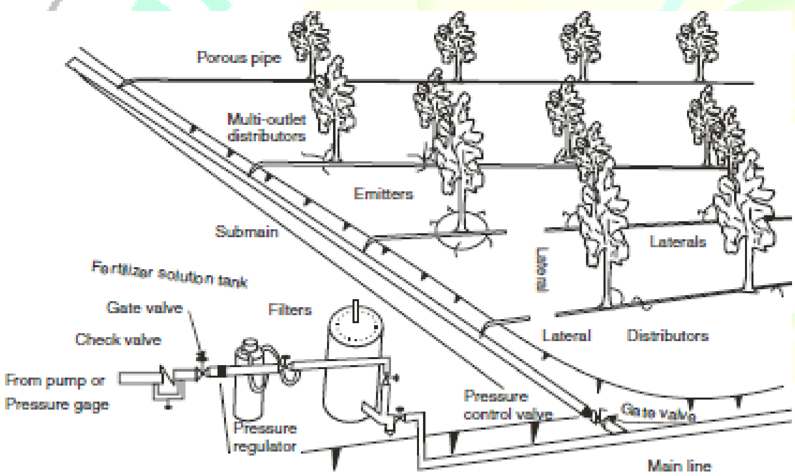


Fig 5.8 Drip irrigation system

The required quantity of water is applied near the root zone alone which in turn save water.

• The root zone is always maintained with field capacity level and hence plants do not suffer for want of water.

• There is no seepage or percolation or evaporation loss.

• Weed growth is restricted due to limited area of wetting zone.

• Fertilizers (fertigation), chemical like pesticides (chemigation) and herbicide (herbigation) can be applied through irrigation. Hence, saving of input quantity and labour cost besides increase in their use efficiencies is possible.

• Reduce the salt content near the root zone and dilute it in saline soil.

• The saline water also can be put under use if irrigation is applied through drip irrigation.

• It can be adopted for any type of topography.

• Yield increases due to optimum maintenance of soil moisture at root zone.

• More area can be maintained with little quantity of water.

• It cab be used for widely spaced crops like cotton, sugarcane, tomato, brinjal, coconut and orchard crops.

Disadvantages

• Clogging in emitters due to salt content of water and other impurities like moss, dust etc.
• Damage of pipe lines by rodents.
• It is not economical for closely spaced crops which require more number of pipes and drippers per unit area.
• Proper maintenance and periodical cleaning of drippers and pipelines (with 1% hydrochloric acid) are very important to maintain the system efficiency.

Chapter 9

Quality of irrigation water

All irrigation waters are not pure and may contain some soluble salts. In arid and semi-arid regions successful crop production without supplemental irrigation is not possible. Irrigation water is usually drawn from surface or ground water sources, which typically contain salts in the range of 200 to 2000 ppm (= 200 to 2000 g/m). Irrigation water contains 10 – 100 times more salt than rain water. Thus, each irrigation event adds salts to the soil. Crop removes water from the soil to meet its water needs (ETc) leaving behind most of the salts to concentrate in the shrinking volume of soil water. This is a continuous process. Application of saline water may hinder the crop growth directly and may also cause soil degradation. Beyond its effect on crop and soil, irrigation water of low quality can also affect environment by introducing potentially harmful substances in to surface and ground water sources. Therefore, a salt balance in the soil has to be maintained through proper water management practices for continuous and successful cultivation of crops.

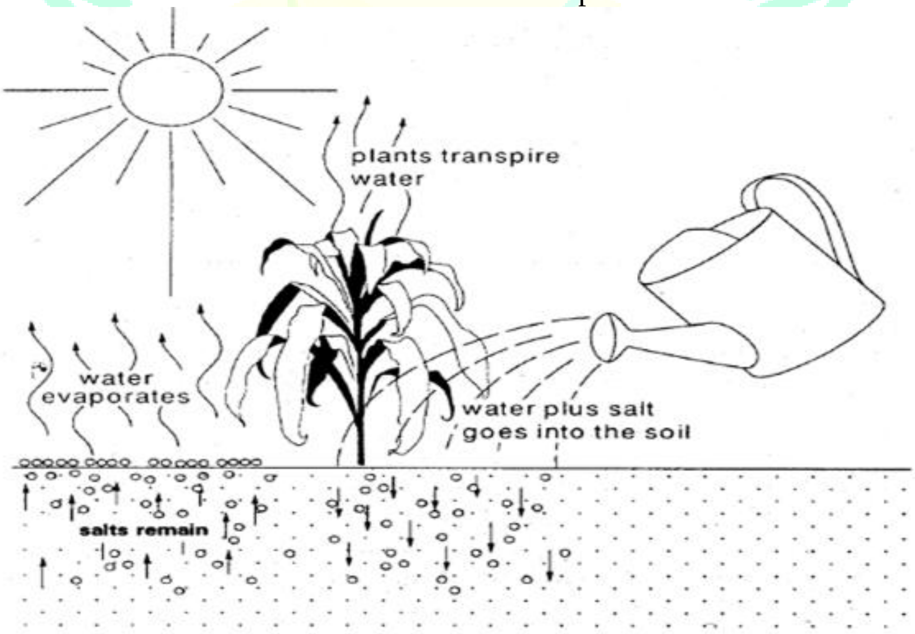


Fig. 8.1 Salinity build up process in irrigated soils

Criteria to determine the quality of irrigation water

The criteria for judging the quality of irrigation water are: Total salt concentration as measured by electrical conductivity, relative proportion of sodium to other cations as expressed by sodium adsorption ratio, bicarbonate content, boron concentration and soluble sodium percentage.

1. Total soluble salts: Salinity of water refers to concentration of total soluble salts in it. It is the most important single criterion of irrigation water quality. The harmful effects increase with increase in total salt concentration. The concentration of soluble salts in water is indirectly measured by its electrical conductivity (ECw). The quality of saline waters has been divided into five classes as per USDA classification given in Table 8.1.

Table 8.1 Salinity classes of irrigation water

Salinity class	Electrical conductivity	
	Micro mhos/cm	Milli mhos/cm
C1 - Low	<250	<0.25
C2 – Medium	25 - 750	0.25 – 0.75
C3 – Medium to high	750 - 2250	0.75 – 2.25
C4 – High	2250 - 5000	2.25 – 5.00
C5 – Very high	>5000	>5.00

Adverse effects of saline water include salt accumulation, increase in osmotic potential, decreased water availability to plants, poor germination, patchy crop stand, stunted growth with smaller, thicker and dark green leaves, leaf necrosis & leaf drop, root death, wilting of plants, nutrient deficiency symptoms and poor crop yields.

2. Sodium Adsorption Ratio (SAR): SAR of water indicates the relative proportion of sodium to other cations. It indicates sodium or alkali hazard.

$$SAR = Na^{+} / \sqrt{(Ca^{++} + Mg^{++}/2)}$$

The ion concentration is expressed as meq per litre. Increase in SAR of water increases the exchangeable sodium percentage (ESP) of soil.

As per USSSL, the sodicity classes of water are shown in Table 8.2

Sodium class	SAR value
S1 – Low	<10
S2 – Moderate	10 – 18
S3 – High	18 – 26
S4 – Very high	>26

Harmful effects of sodic water include destruction of soil structure, crust formation, poor seedling emergence, and reduction in availability of N, Zn and Fe due to increased soil pH, Na toxicity and toxicity of B & Mo due to their excessive solubility.

3. Residual sodium carbonate: Bicarbonate is important primarily in its relation to Ca and Mg. There is a tendency for Ca to react with bicarbonates and precipitate as calcium carbonate. As Ca and Mg are lost from water, the proportion of sodium is increased leading to sodium hazard. This hazard is evaluated in terms of Residual Sodium Carbonate (RSC) as given below:

$$RSC\ (meq/litre) = (CO_3^{--} + HCO_3^{-}) - (Ca^{++} + Mg^{++})$$

RSC is expressed in meq per litre. Water with RSC more than 2.5 meq/L is not suitable for irrigation. Water with 1.25 to 2.5 meq/L is marginally suitable and water with less than 1.25 meq/L is safe for use.

4. Boron content: Though boron is an essential micronutrient for plant growth, its presence in excess in irrigation water affects metabolic activities of the plant. For normal crop growth the safe limits of boron content are given in Table 8.3.

Table 8.3 Permissible limits of boron content in irrigation for crops

Boron (ppm)	Quality rating
<3	Normal
3 – 4	Low
4 – 5	Medium

5 – 10	High
More than 10	Very high

Leaching requirement

Leaching requirement (LR) is that fraction of total crop water requirement which must be leached down below the crop root zone depth to control salts within the tolerance level (ECe) of the crop.

$$\text{Leaching Requirement (LR)} = ECw/(5(ECe) - Ecw)$$

Where:
ECw = Salinity of applied water in dS/m
ECe = Threshold level soil salinity of the crop in dS/m

Management practices for using poor quality water

Whenever, it is inevitable to use water of poor quality water for crop production appropriate management practices helps to obtain reasonable yield of crops. Some of the important management practices are as follows:

a. **Application of gypsum:** Chemical amendments such as gypsum, when added to water will increase the calcium concentration in the water, thus reducing the sodium to calcium ratio and the SAR, thus improving the infiltration rate. Gypsum requirement is calculated based on relative concentration of Na, Mg & Ca ions in irrigation water and the solubility of gypsum. To add 1 meq/L of calcium, 860 kg of gypsum of 100% purity per ha m of water is necessary.
b. **Alternate irrigation strategy:** Some crops are susceptible to salinity at germination & establishment stage, but tolerant at later stage. If susceptible stages are ensured with good quality water, subsequent tolerant stages can be irrigated with poor quality saline water.
c. **Fertilizer application:** Fertilizers, manures, and soil amendments include many soluble salts in high concentrations. If placed too close to the germinating seedling or to the growing plant, the fertilizer may cause or aggravate a salinity or toxicity problem. Care, therefore, should be taken in placement as well as timing of fertilization. Application of fertilizers in small doses and frequently improve uptake and reduce damage to the crop plants. In addition, the lower the salt index of fertilizer, the less danger there is of salt burn and damage to seedlings or young plants.
d. **Methods of irrigation:** The method of irrigation directly affects both the efficiency of water use and the way salts accumulate. Poor quality irrigation water is not suitable for use in sprinkler method of irrigation. Crops sprinkled with waters having excess quantities of specific ions such as Na and Cl cause leaf burn. High frequency irrigation in small amounts as in drip irrigation improves water availability and uptake due to microleaching effect in the wetted zone.
e. **Crop tolerance:** The crops differ in their tolerance to poor quality waters. Growing tolerant crops when poor quality water is used for irrigation helps to obtain reasonable crops yields. Relative salt tolerance of crops is given in Table 26.4.
f. **Method of sowing:** Salinity reduces or slows germination and it is often difficult to obtain a satisfactory stand. Suitable planting practices, bed shapes, and irrigation management can greatly enhance salt control during the critical germination period. Seeds have to be placed in the area where salt concentration is less. Salt accumulation is less on the slope of the ridge and bottom of the ridge. Therefore, placing the seed on the

slope of the ridge, several cm below the crown, is recommended for successful crop establishment.

Table 8.4 Relative salt tolerance of crops

Tolerant	Field crops: Cotton, Safflower, Sugarbeet & Barley Fruit crops: Date palm & Guava Vegetables: Turnip & Spinach Forage crops: Berseem & Rhodes grass
Semi tolerant	Field crops: Sorghum, Maize, Sunflower, Bajra, Mustard, Rice & wheat Fruit crops: Fig, Grape & Mango Vegetables: Tomato, Cabbage, Cauliflower, Cucumber, Carrot & Potato Forage crops: Senji & Oats
Sensitive	Field crops: Chick pea, Linseed, Beans, Greengram & Blackgram Fruit crops: Apple, Orange, Almond, Peach, Strawberry, Lemon & Plum Vegetables: Radish, Peas & Lady's finger

g. **Drainage:** Provide adequate requirement depending on crop and EC of water. This is necessary to avoid build of salt in the soil solution to levels that will limit crop yields. Leaching requirement can be calculated from water test results and tolerance levels of specific crops.

h. **Other management practices**

1) Over aged seedlings in rice: Provide adequate internal drainage. Meet the necessary leaching depending on crop and EC of water. This is necessary to avoid build of salt in the soil solution to levels that will limit crop yields.
2) Mulching: Mulching with locally available plant material help in reducing salt problems by reducing evaporation and by increasing infiltration. Mulching with locally available plant material help in reducing salt problems by reducing evaporation and by increasing infiltration.
3) Soil management: All soil management practices that improve infiltration rate and maintain favourable soil structure reduces salinity hazard. soil management practices that improve infiltration rate and maintain favourable soil structure reduces salinity hazard.
4) Crop rotation: Inclusion of crops such as rice in the rotation reduces salinity. Inclusion of crops such as rice in the rotation reduces salinity.

Chapter 10

Weed and its classification

Definition of a Weed:

Undesirable and unwanted plants growing out of their proper place

Or

A plant which grows voluntarily at places where it is not wanted and grows at places where other useful plants grow

Or

A weed is a plant which interferes with human activity or welfare.

Origin and Evolution of weeds:-

In stable (climax) vegetation, all plant species are equally naturally adapted.

Weeds evolved

i. When the stable environment is disturbed through human activities.
ii. Fromecotypes that have evolved from wild colonizers in response to continuous habitat disturbances and selection pressures.
iii. As a result of the products of hybridization between wild domestic races of crop plants.

Characteristics of Weeds

- Can tolerate adverse climatic conditions
- Competitive and aggressive in nature
- Resist control/eradication
- Morphological similarities
- High reproductive capacity
- Persistent in nature
- Early seed setting
- Repeated germination in different phases
- Deep root system
- Similarity of seed
- Seed dormancy: could be innate, induced or enforced.

Harmful effect of weed-

Weeds have serious impacts on agricultural production. It is estimated that in general weeds cause 5% loss in agricultural production in most of developed countries, 10% lossin less developed countries and 25% loss in least developed countries. In India, yield losses due to weeds are more than those from pest and diseases. Yield losses due to weeds vary with the crops. Every crop is exposed to severe competition from weeds. Most of these weeds are self-sown and they provide competition caused by their faster rate of growth in the initial stages of crop growth. In some crops, the yields are reduced by more than 50% due to weed infestation.

Reduction in crop yield through:-

Physical Interaction (Allelospoly: competition for growth resources including water, light, nutrient, air, space.Chemical interaction (Allelopathy)

Reduction in crop quality through

- Direct contamination of cultivated rice and maize grain by wild rice(*Oryza longistaminata*) and itch grass (*Rottboelliaco chinchinensis*) respectively

- Contamination of forage, silage or pasture crop .by *C. rotundus* seeds.

-Reduction in Sugarcane juice quality bythe presence of sida.

-Contamination of cotton lint by dried weed fragments

-Damage of underground tuber of yam and cassava through piercing of Spear grass rhizomes

- Interference with field operations (harvest,pesticideapplication,etc.)
- *Some are poisonous to grazing animals* e.g. *Euphorbia heterophylla, Halogetonglomeratus* contain high oxalate content, it can kill livestock when eaten in dry season.
- Weeds compete with crops for water soil, nutrients, light, and space, and thus reducethe crop yields.
- Some are harmful to grazing animals e.g. *Amaranthus spinosus, Acanthospermum hispidus*
- Increase cost of production; high cost of labour and equipment during harvesting.
- Presence of weeds can impede water flow in irrigation canals
- Weeds present in lakes and reservoirs can increase loss of water by evapo-transpiration
- Reduction in quality of pasture land; it reduces the carrying capacity of grazing lands and pastures through their physical presence and weediness
- Reduction in quality of animal products;it affects the palatability of pastures, hay; silage etc. protein content in alfalfa wild garlic (Alliums spp) when eaten by cattle spoils the meat and the milk.
- Weeds reduce the quality of marketable agricultural produce.
- Serve as alternate hosts for many plant diseases and animal pests e.g. insects, rodents, birds. *Cyperusrotundus* serve as alternate to nematodes and athropods
- Impose limitation to the farm size of a farmer
- Can serve as sources of fire hazards

Beneficial Effects of Weeds:-

In spite of all the difficulties caused by weeds, they can offer some beneficial properties,particularly when occurring at low densities. These aspects should be utilised in the farmingsystem, although this may make organic management more complicated than chemical basedsystems. Some of the potential benefits of weeds are listed below:

- Helping to conserve soil moisture and prevent or Reduce erosion problem through the production of protective cover
- Help in nutrient recycling through decay of vegetative part.
- Food/vegetables for humans e.g. leaves of *Talinumtriangulare*, and tubers of *Colocasiaesculentus* .
- Serve as hosts and nectar for beneficial insects
- Beautification of the landscape e.g. *Cynodondactylon*
- Feed for livestock and wildlife and aquatic organisms in form of hay, silage and forage / pasture, fruit seeds and branches and whole plant.
- Source of pesticides e.g. *Chrysanthemum cinerariifolium*
- Source of genetic material for useful traits in crop improvement.
- Medicinal use e.gneem (*Azadirachtaindica), Ageratum conyzoides*
- Some serve as trap crop for parasitic weeds.
- Habitat for wildlife and plant species hence biodiversity conservation.

- Major role in carbon recycling through carbon sequestration. Field of exposed soil always suffers a net loss in organic matter and releases carbon dioxide, while a field covered with crops and/or weeds takes up carbon dioxide. This concept of carbon sequestrations an added advantage of sustainable and organic farming.

Classification of weeds

Weeds can be classified based on :

Life cycle or history (Ontogeny): Annual, Biennials and Perennial weeds

a. **Annual Weeds**

Weeds that live only for a season or a year and complete their life cycle in that season or year are called as annual weeds.

Kharif annuals:-Exa. *Digeraarvensis, E. crusgalli*

Rabi annuals:-Exa. *Phalirs minor, Chenopodium album*

b. **Biennials weeds:-** Exa. *Daucuscarota, Cirsiumvulgare*

c. **Perennial weeds:-**Exa.*Cyperusrotundus, Sorghum halepense*

2. **Based on Habitat:-**
   a. *Upland (terrestrial*) weeds or dry land weeds (Agrestal /Weeds of arable or cultivated crops, andRuderal weeds /weeds of disturbed non- cropped area such as rubbish heaps, landfills, paths, roads, compost heaps
   b. *Aquatic weeds* (Submerged aquatic, Floating aquatic, Emergent aquatic weeds

3. **Based on soil type (Edaphic)**
   a. **Weeds of black cotton soil:** These are often closely allied to those that grow in dry condition. Eg., *Aristolo chiabracteata*
   b. **Weeds of red soils:** They are like the weeds of garden lands consisting of various classes of plants. Eg. *Commelina benghalensis*
   c. **Weeds of light, sandy or loamy soils:** Weeds that occur in soils having good drainage. Eg. *Leucas aspera*
   d. **Weeds of laterite soils:** Eg. *Lantana camara, Spergula arvensis*

4. **Based on Growth habit:**
   Free living (autotrophic) weeds
   Parasitic plants(*Root parasitic weed*s or *obligate parasite, Stem parasitic weeds, Semi parasitic weeds, Total parasites* floating aquatic Emergent aquatic weeds
5. **Based on Degree of undesirability:** ease and difficulty in controlling weeds.
6. **Based on Morphology** *:*
   e.g. i. Woody Stem e.g*Azadirachta indica,*
   ii. Semi Woody weeds- e.g*Chromolaena odorata, Sidaacuta.*
   *iii.*Herbaceous weeds*: e.g Ageratum conyzoides, Talinum triangulare,*
   b.Leaf Type: i) Narrow leaf: grass like (ii) Broad leaf weeds (Dicotyledons):, Sedges; e.g. *Cyperusrotundus, C. esculentus, Mariscusalternifolius*
7. Scientific classification (Binomial nomencIture): based on their taxonomy (family, genera and specific epithet
8. Ecological affinities: dryland weeds, gardenland weeds and wetland weeds

Chapter 11

Weed management

Crop –weed competition

When plants grow close to each other, they interact in various in ways.

Interference: It is the detrimentaleffects of one species on another resultingfrom their interactions with each other. When plants are far apart they have no effect on each other. Interaction generally involves competition and amensalism.

Commensalism: This is the relationship between unrelated organism (different species) in which one derives food or benefit from the association while the other remains unaffected.

***Competition* (allelospoly)**: It is the relationship between two plants (weed/crop, crop/crop, weed/weed) in which the supply of a growth factor falls below their combined demand for normal growth and development. The growth factor competed for include water, nutrients, light, space and air/gasses (oxygen, carbon dioxide).

Types of competition

- Above-ground (Aerial) competition Takes place in the leaves and the growth factors involve are light and carbon dioxide.
- Below-ground(Subterranean) competition: Takes place mainly in the roots while the growth factors involve are water, nutrients and oxygen.
- The perceived consequence of competition with crop is reduction in the economic yield of affected crop plants.

Forms of competition:

Intraspecific competition: competition for growth factors among individuals of a plant species

Interspecific competition: competition for growth factors between two different plant species i.e., crop/weed, weed/weed,or crop/crop.

Critical Period of Weed competition/interference:

This is the minimum period of time during which the crop must be free of weeds in order to prevent loss in yield.

a. It represents the overlap of two separate components (a) the length of time weeds can remain in a crop before interference begins
b. The length of time that weed emergence must be prevented so that subsequent weed growth does not reduce crop yield.

Factors affecting weed-crop competition

- Competitiveness of weed species
- Weed density and weight
- Onset and duration of weed-crop association
- Growth factors
- Type of crop and seeding rate
- Spatial arrangement of crops
- Plant architecture
- Growth factors availability
- Cropping patterns
- Crop type (C3 or C4 plants)
- Crop variety(tolerance, resistance, aggressiveness)

Environmental factors

- Climatic factors e.g. rainfall, temperature, wind, light etc
- Tillage
- Ground water management
- Soil (Edaphic)

- ***Amensalism*** (**Allelopathy**)
- **Allelopathy**is the production of chemical(s) or exudates by living and decaying plant species which interfere with the germination, growth or development of another plant species or microorganism sharing the same habitat.

There are two types of allelopathy:(***True and Functional***)

True allelopathy involves the release into the environment compounds that are toxic in the form they are produced. *Functional allelopathy*involves the release into the environment substances that are toxic as a result of transformation by microorganism.

Allelochemical complex commonly encountered in plants include:

coumaric acid, terpenoids, - syringic acid, butyric acid, flavonoids, phenolic compounds.

Examples of allelopathic plants:

1. Black walnut (*Juglansnigra*)
2. *Gmelinaarborea*
3. *Soghum bicolor*
4. Casuarina
5. *Lantana camara*
6. *Imperatacylindrica* is allelopathic on tomato, cucumber, maize rice, glnut, olera, cowpea, pepper.
7. *Cyperusesculentus*– is allelopathic on rice, maize
8. *C. rotundus* – is allelopathic on barley.

- ***Parasitism***- It is a relationship between organisms in which one lives as a parasite in or on another organism.
- ***Parasitic* weeds** are plants that grow on living tissues of other plants and derive part or all of their food, water and mineral needs from the plant they grow on (host plants)
- ***Hemi parasite*** (*Semi parasite*) a plant which is only partially parasitic, possessing its own chlorophyll (green colour) and photosynthetic ability (may be facultative or obligate). e.g*Strigahermonthica*
- ***Holo parasite*** – a plant which is totally parasitic, lacking chlorophyll thus unable to synthesize organic carbon. E.g*Orobanchespp*
- ***Obligate parasite*** – a plant which cannot establish and develop without a host
- ***Facultative parasite*** – a plant which can grow independently but which normally behaves as a parasite to obtain some of its nutrition.
- ***Predation***: It is the capture and consumption of organisms by other organisms to sustain life.
- **Mutualism**: It is an advantageous relationship between two organismsof different species that benefits both of them. It is obligatory and the partners are mutually dependent. Both partners are stimulated when the interaction is on. Example is the case between fungus and algae. The fungus protects the algae while the algae provide carbohydrate for the fungus.
- **Neutralism:** This is the situation where plant exert no influence on one another.

- **Protocooperation:** This is a condition whereby two plants interact and affect each other reciprocally. Both organisms are stimulated by the association but unaffected by its absence.

Weed management- Principles and methods

Weed Management refers to how weeds are manipulated so that do not interfere with the growth, development and economic yield of crops and animals. It encompasses all aspects of weed control, prevention and modification in the crop habitat that interfere with weed ability to adapt to its environment.

Weed control: Refers to those actions that seek to restrict the spread of weeds and destroy or reduce their population in a given location. The effectiveness of weed control is affected by

i. Type of crop grown
ii. Timing of weeding operation
iii. Nature of the weed problem
iv. Methods of weed control available to the farmer
v. Type of weeds to be controlled
vi. Cost of the operation
vii. Available labour or cash resources
viii. Environmental condition before during and after the time of operation.

Weed prevention: This refers to the exclusion of a particular weed problem from the system that has not experienced that weed problem. It involves those measures necessary to prevent the introduction of new weed species into a given geographical area as well as the multiplication and spread of existing weed species.

It includes the following:

Fallowing
Preventing weeds from setting seeds
Use of clean crop seed for planting
Use of clean machinery
Controlling the movement of livestock
Quarantine laws services

Weed eradication: This involves complete removal of all weeds and their propagules from a habitat.Eradication is difficult to achieve in crop production and uneconomical. However in situations where weed problem becomes so overwhelming, eradiation may be desirable in long term goal. E.g. *Strigaasiatical, S. hermonthica*.Eradication may be considered if :

i. Other weed control methods are ineffective
ii. Weeds have many buried seeds that cannot be controlled by conventional practice.
iii. The infested field is small
iv. Benefits from eradication outweigh those of the alternate methods for copping with weeds.

Methods of weed control: -

1. **Physical –**
   a. Tillage
   b. Hand pulling
   c. Hand hoeing
   d. Inter culture
   e. Flooding
   f. Flaming
   g. Mowing

2. **Cultural Method –**
   a. Crop rotation
   b. Date of sowing
   c. Plant density
   d. Planting pattern
   e. Methods of fertilizer application
   f. Selection of quick growing varieties
   g. Dab system
   h. Mulching
   i. Irrigation management
   j. Soil solization

3. **Chemical methods**

   Histories of herbicides/chemical weed control

- The use of chemical weed control started with inorganic copper salts e.g $CuSO_4$ for broadleaf weed control in cereals in Europe in 1896.
- Other inorganic salts that were tested between 1900-1930 included nitrates and borates.
- In 1912, sulphuric acid (H_2SO_4) was used for selective weed control in onions and cereals. In 1932, the first organic herbicide, Dinitro-ortho Cresol (DNOC) was introduced.
- In the 1950s triazine was introduced. In 1974, Glyphosate, frequently sold under brand name Roundup for non-selective weed control was introduced.
- Agriculture witnessed tremendous changes through the production of organic herbicides, which came at a time when field workers were reducing, high cost labour and productive cost of production. Thus, farmers in advance countries almost depended on herbicide because it met their production challenges in agriculture and relatively ignored other methods of weed control.

- Limitation of chemical methods –
  - Lack of application technology.
  - Weed resistance
  - Herbicide drift
  - When crop fails no choice for succeeding crops
  - Chemical crop war
  - Cost of few herbicides is high
  - Pollution hazards

4. Biological methods: - This method is an effective, environmentally safe, technical appropriate, economical viable and socially acceptable methods of weed management.

Qualities of bio agents

a. Host specific
b. Adjustment to field environment
c. Easy to multiply
d. Feeding habbits

Kinds of bio agents

a. Insects
b. Plant pathogens

c. Carp fish
d. Competitive plants

Integrated weed management

- **a.** This method is more effective because the left over weeds with one methods can be controlled with other methods. So this methods helps in reducing seed bank status in the field.
- **b.** Many problems such as shift in weed flora, development of resistance in weed plants etc. can be avoided.
- **c.** IWM approaches are environment friendly as farmers should not entirely depends on herbicide.
- **d.** No danger of herbicide residue in soil or plant.
- **e.** It is very suitable for high cropping intensity

Higher net returns are achieved with the adaptation of this method

Chapter 12

Herbicide classification

Herbicides- classification

Herbicides are classified according to their:-

- Selectivity
- Mode of action
- Timing of application.
- Chemical group
- Mechanism of action

SELECTIVITY

1. A **non-selective** herbicide kills or damages all plant life in a treated area (e.g., Roundup).
2. A **selective** herbicide will kill weeds in a germinating or growing crop without harming the crop beyond the point of recovery (e.g., 2,4-D used to control broadleaved weeds in a grass pasture; Avadex to control wild oats in cereals.)

MODE OF ACTION (or how the herbicide works to kill a weed)

1. **Contact herbicides –** kills plant parts covered by the herbicide and are directly toxic to living cells. There is little or no translocation or movement of the material through the plant. Contact herbicides are effective against annual weeds but they only "burn off" the tops of perennial weeds – chemically mowing them. **Contact herbicides may be selective, such as Torch (bromoxynil)** which kills broadleaved weeds in cereals without damaging the crop, **or nonselective, such as Gramoxone (paraquat)** which kills any green plant material.
2. **Systemic herbicides** – absorbed by either the roots or above ground parts of plants, these herbicides move or are translocated in the plant. They exhibit a chronic effect; that is, the full effects may not show for a week or more after treatment. An overdose on the leaves may kill the leaf cells more quickly, thus preventing translocation to the site of action in a plant. **Systemic herbicides can be selective, as in the case of 2,4-D, MCPA, Banvel and Tordon or non-selective, as with Roundup.**
3. **Soil Sterilants**– chemicals which prevent growth of plant life when present in the soil. These products will prevent plant growth for periods of a few months to a number of years. Examples include bromacil, tebuthiuron and atrazine at high rates.

TIMING OF APPLICATION

1. **Pre-Plant Soil Incorporated** – these herbicides are applied to the soil before the crop is sown. They are incorporated in the soil to prevent loss due to vapourization and breakdown by sunlight. Trifluralin and EPTC are examples.
2. **Pre-Emergence** – applied to soil prior to seeding or after the crop is sown but before crop and weeds emerge. In most cases, the weeds germinate in treated soil while the crop germinates below the herbicide zone.
3. **Post-Emergence** – sprayed directly on the weeds after they are up and growing.

Comparison of Soil-Applied and Foliar-Applied Herbicides
Source: Weeds '81 Alberta Agriculture

HERBICIDE TYPE: *PRE-PLANT INCORPORATED* (Soil Applied)
Advantages:
1. Early control of weeds, minimizing competition.
2. Weeds are controlled where wet or windy weather after emergence can delay spraying.
3. Work load is distributed.

Disadvantages:
1. Perennial weeds are generally not controlled.
2. Less effective under dry or cold soil conditions.
3. Residue may restrict crop rotation the following year.
4. Soil erosion may be a problem, as additional tillage for incorporation is required.

HERBICIDE TYPE: *PRE-EMERGENCE INCORPORATED* (Soil Applied)
Advantages:
1. Early control of weeds, minimizing competition.
2. Weeds are controlled where wet or windy weather after emergence can delay spraying.
3. Planting and herbicide application may be done in one operation.

Disadvantages:
1. Less effective under dry or cold soil conditions.
2. Perennial weeds are generally not controlled.
3. On sandy soils, heavy rains may leach the herbicide down to the germinating crop and cause injury.
4. Wet or windy conditions after seeding can delay application until crop emergence and prevent herbicide application.
5. Planting may be slowed down by combining planting and herbicide application.
6. Residue may restrict crop competition the following year.
7. Soil erosion may be a problem, as additional tillage for incorporation is required.

HERBICIDE TYPE: *POST-EMERGENCE (*Foliar applied)
Advantages:
1. Type and density of weed can be seen before herbicide application.
2. Soil texture does not directly affect herbicide choice or performance.
3. Soil moisture has little influence on level of control.
4. Few post emergent herbicides leave a soil residue which will restrict subsequent cropping rotation.
5. Incorporation tillage is not required.

6. Top growth control of several perennial weeds is possible.

Disadvantages:

1. Specific stage of application required on both crop and weed variable emergence may be a problem.
2. Flush of weeds after spraying generally not controlled.
3. Wet or windy weather can delay application.

Based on Mechanism of action

Mechanism of action	Chemical family	Active ingredients
Inhibitors of acetyl CoA carboxylase ACCase. These chemicals block an enzyme called ACCase. This enzyme helps the formation of lipids in the roots of grass plants. Without lipids, susceptible weeds die.	Aryloxyphenoxy propionate (Fop)	clodinafop-propargyl
		fenoxyprop-p-ethyl
		quizalofop-p-ethyl
	Cyclohexanediones (Dim)	clethodim
		sethoxydim
		tepraloxydim
		tralkoxydim
	Phenylpyrazolin (Den)	pinoxaden
ALS/AHAS inhibitors. These chemicals block the normal function of an enzyme called acetolactate (ALS) actohydroxy acid (AHAS). This enzyme is essential in amino acid (protein) synthesis. Without proteins, plants starve to death.	Imidazolinones	AC 299, 263, 120 AS
		imazamethabenz
		imazamox
		imazamox + imazethapyr
		imazapyr
		imazethapyr
	Sulfonylamino-carbonyltriazolinones	flucarbazone sodium
	Sulfonylureas	chlorsulfuron
		ethametsulfuron methyl
		metsulfuron-methyl
		nicosulfuron
		rimsulfuron
		thifensulfuron-methyl
		tribenuron-methyl
		triflusulfuron methyl
	Triazolpyramidines	florasulam
		pyroxsulam
	Triazolones	thiencarbazone-methyl
Microtubule assembly inhibitors. These chemicals inhibit the cell division in roots.	Dinitroanilines	ethalfluralin
		trifluralin
Synthetic auxins. These chemicals disrupt plant cell growth in the newly forming stems and leaves; they affect protein synthesis and	Benzoic acids	dicamba
	Carboxylic acids	clopyralid
		aminopyralid

normal cell division, leading to malformed growth and tumors.		fluroxypyr
		picloram
	Phenoxy	2,4-D
		dichlorprop (2,4-DP)
		2,4-DB
		MCPA
		MCPB
		mecoprop (MCPP)
		quinclorac
Photosynthetic inhibitors at Photosystem II, Site A. These chemicals interfere with photosynthesis and disrupt plant growth, ultimately leading to death.	Phenyl-carbamates	desmedipham
		phenmedipham
	Triazines	atrazine
		simazine
	Triazinones	hexazinone
		metribuzin
		pyrazon
	Uracils	bromacil
Photosynthetic inhibitors at Photosystem II, Site II	Benzthiadiazoles	bentazon
	Nitriles	bromoxynil
Photosynthetic inhibitors at Photosystem II, Site B.	Ureas	diuron
		linuron
Lipid synthesis inhibitors (not ACCase inhibition). These chemicals inhibit the cell division and elongation in the seedling shoots before they emerge above ground.	Thiocarbamates	EPTC
		triallate
	Pyrazolium	difenzoquat
Inhibitors of EPSP synthesis. These chemicals inhibit the amino-acid synthesis.	None	glyphosate
Inhibitors of glutamine synthetase.	None	glufosinate-ammonium
Carotenoids biosynthesis inhibitors. These chemicals inhibit the carotenoids biosynthesis.	Triazole	amitrol
Inhibitors of cell growth and division.	Chloroacetamides	metolachlorpropyzamide
Cell membrane disrupters. (Inhibitors of P.S.-I) Chemicals that disrupt the internal cell membrane and prevent the cells from manufacturing food.	Bipyridyliums	diquat paraquat

Based on chemical groups

1	Aliphatic acids	Dalapon, FCA, Glyphosate, Methyl bromide, Cacodylic acid, MSMA, DSMA
2	Amides	Alchlor, Butachlor, Propachloi, Metalachlor, Diphenamide. Propanil
3	Benzoics	2,3,6, TBA, Dicamba, tricamba. Chloramben
4	By Pyridillums	Paraquat, Diquat
5	Carbamates	Prop ham, Chlorpropham. Barban. Dichlormate. Asulam
6	Thiocarbamates	Butylate, Diallate, EPTC, Molinate, Triallate, Benthiocarb, Metham
7	Dithiocarbainates	CDEC, Metham
8	Nitriles	Bromoxynil, Ioxynil, Dichlobenil
9	Dintroanilins	Fluchloralin, Trifluralin, Pendimethalin, Nitralin, Isoproturon
10	Phenols	Dinoseb, DNOC, PCP
11	Phynoxy acids	2,4 D, 2,4,5-T, MCPA, MCPB, 2,4-DB, Dichlorprop
12	Traizines	Atrazine, Simazine, Metribuzine, Amytrin, Terbutrin
13	Ureas	Monuron, Diuron, Linuron, Metoxuron, Isoproturon, Methabenz thiozuron
14	Uracils	Bromacil, Terbacil, Lenacil
15	Diphenyl ethers	Nitrofen, Oxyfluorfen, Nitrofluorfen
16	Aryloxyphenoxy propionate	Diclopop Fenoxaprop-p, Quizalofop-p, Haloxyfop-p, Fluazifop-p
17	Cyclohexanedione	Sethoxydim, Clethodim, Tralkoxydim, Cycloxidim
18	Imidazolines	Imazapyr, Imazamethabenz, Imazaquin, Imazamax, Imazethapyr
19	Isoxazolidinones	Clomazone
20	Oxadiazoles	Oxadiazon
21	Oxadiazolides	Methazole
22	N-phenylphthalamides	Flumiclorac
23	Phenylpyridazones	Sulfentrazone
24	Phthalamates	Naptalam
25	Pyrazoliums	Difenzoquat, Metflurazone
26	Picolinic acids Pyridine	Picloram, Dithiopyr, Pyrithiobac, Fluridone, Thiazopyr
27	Quinolines	Quinclorac
28	Sulfonylureas	Bensulfuron, Chlorimuron, Metsulfuron, Sulfosulfuron, Triasulfuron
29	Triazolinones	Pyridates
30	Cineoles	Cinmethylin
31	Others	Pichloram, Pyrazon, Endothal, Oxadiazon, Amitrole, Anilofos

Herbicide Selectivity

It is a phenomena by which in a given mixed crop stand some species eg weeds are preferably controlled while others (eg crops) remains unaffected or marginally affected when a herbicide is applied to them.

Selectivity Index (S.I.)

$$S.I. = \frac{\text{Max. dose of herbicide tolerated by crop}}{\text{Min dose of herbicide required to control weed}}$$

If SI <2 it is safe for use.

Fundamental principle of selectivity:

More toxicant reaches to the active site of action in more active form inside the target species than in non-target species.

Selectivity mechanism

1. Differential absorption
2. Differential translocation
3. Differential metabolism

Differential absorption

Eg. 2,4-D slow absorbed in wild cucumber ((*Sicyos angulatus*) and makes it tolerant to 2,4-D whereas quick absorption in cucumber (*Cucumis sativa*) makes it susceptible.

Causes:

- ❖ Difference in morphology & growth
- ❖ Difference in time and method of application
- ❖ Difference in herbicide formulation
- ❖ Use of absorbents and antidotes

Difference in morphology & growth

It causes differential retention of aquas spray. Limited retention of spray may cause due to:

- ❖ Narrow upright leaves
- ❖ Corrugated/ finely ridged leaf surface
- ❖ Waxy leaf surface
- ❖ Pubescent leaves

These protects against contact and selective herbicides but not useful for translocated herbicides.

Difference in growth habit:

- ❖ Directed spray in a situation where high crops and short weeds exist.
- ❖ Herbicide mulch in standing crop row can cause effective control of germinating weeds.
- ❖ In case of slow germinating crops like sugarcane, potato etc weeds germinate before crop emergence. In that case spray of selective and contact herbicides can selectively control weeds.
- ❖ **Depth protection:** Weed seed bank exists between top 1.25 – 1.5 cm of soil whereas crop seeds are placed in 5.0 cm depth. In this case pre-emergence herbicide which leaches upto 2.5 cm can kill weeds but cannot reach upto the depth where crop seeds exist. **This is the basic selectivity mechanism of all pre-emergence herbicides.**

Eg. Selectivity of Monilate between rice and *Echinochloa*

Use of absorbents and antidotes

Absorbents like activated charcoal is a strong absorbent of 2,4-D., Butachlor. Germinating seedlings surrounded by layer of activated charcoal escape phyto toxicity of several herbicides.

Herbicide formulation

Granular formulation of herbicides imparts selectivity in case of cotton against Diuron. It filters through crop foliage and accumulates in moist ground and finally absorbed by weeds and kill them.

Differential translocation

Eg. 2,4-D slowly translocated in sugarcane (tolerant) but quickly translocated in beans (Susceptible).

Differential metabolism:

In this case herbicides are converted in non-phytotoxic compounds inside the non targeted species while it becomes phytotoxic in susceptible species.

There are several mechanisms of metabolism:

1. **Conjugation:** Coupling of intact herbicide molecule with some plant cell constituent in living plants. It takes phyto toxic compounds out of the main stream of plants and thus become tolerant.

Eg. Selectivity of Atrazine in sorghum due to conjugation of Atrazine in sorghum leaf by the enzyme **Glutathione-S-Transferase (GST) enzyme**.

2. **Hydroxylation:** Selectivity of Atrazine in maize due to hydroxylation of Atrazine in maize roots by the enzyme **Benzoxazinone.**

3. **Hydrolysis:** Selectivity of Propanil between Echinochloa and rice is due to hydrolysis of Propanil in rice due to presence of an enzyme called **Aryl- acyl amidase.**

4. **Oxidation:**

   ❖ Selectivity of 2,4DB, MCPB, MCPA in leguminous crops is due to β-oxidation of these herbicides in non-leguminous weeds which makes them more phytotoxic than the parent compounds. This is called **reverse metabolism**.

   ❖ Selectivity of Isoproturon between wheat and Phalaris is due to presence of P-450 monooxygynase in wheat which oxidizes the compound.

5. **N-Dealkylation:** Substitution of alkyl groups from N –position of several herbicides.

   Eg. Selectivity of Monuron/Diuron in cotton.

Herbicide resistance & its management

Herbicide resistance is a phenomenon by which a plant/biotype is capable to survive and reproduce seeds even after a exposure to a dose of herbicide normally lethal to the wild type.

Herbicide resistance is measured by Resistance Factor (GR_{50}) values – based on the % inhibition of growth / dry wt. of plant.

$$GR_{50} = \frac{GR_{50} \text{ values of resistant population}}{GR_{50} \text{ values of susceptible population}}$$

Types of resistance : -

1. **Cross resistance:** - It is the resistance of a weed biotype to two on more herbicides of same on different chemical groups having the same mode of action **by a single resistance mechanism.**

   Cross resistance evolve when a weed biotype already resistant to a herbicide shows resistance to other herbicides of same/ different chemical groups to which it had never been exposed.

   Eg:- *Phalaris minor* – already resistant to Isoproturon shows resistance to dictofop methyl, clodina-fop prropargyl

   Multiple resistance: - It refers to the herbicide resistance where a weed species shows resistance to two or more herbicides of different chemical class having two distinctly different mode of action through **two different resistance mechanism.**

   Eg: - *Lolium rigidum* in Australia

   Factors affecting herbicide resistance : -

a. Weed factors

1. **Initial frequency of resistant weed species in a mixed population**: - Higher the initial frequency greater & quicker is the chance of developing resistance.
2. **Hypersensitivity of weed spp**. :- Some weed sp. are hypersensitive to a particular herbicide which – kills – 90-95 % of its susceptible population with a single application. In this case selection – pressure is higher & there is quicker chance of resistance development.
3. **Biological fitness**: - It is the relative evolutionary advantages of a phenotype based on its survival and reproductive success. If a resistant biotype is biologically more fit – there is quicker establishment of resistance.
4. **Weed biology** (seed dormancy, germination, mode of pollination, seed production capacity) & soil seed bank.

   The development of resistance gets delayed if continuous recruitment of susceptible individuals takes place from the soil seed bank by presowing tillage. This is further influenced by dormancy germination characteristics of weed seeds, their seed production ability etc.
5. Mode of inheritance of gene : - Inheritance of a single gene which confer resistance against herbicide for a specific target site may dominate under field condition, inherit and express readily under heterozygous condition resulting from out crossing of weeds at field level.

b. Herbicide factor:-

1. **Application of highly potent herbicide**: - It increases selection pressure of resistance biotypes and increase resistance.
2. **Application of herbicide having a single target site specific mode of action: -** Frequently application of such herbicides over locations imparts high selection pressure towards evolution of resistance weed biotypes.
3. **Overdependence and frequent application of herbicide without rotation**.
4. **Application of herbicide having longer residual activity on soil.**
5. **Time & dose of application**.

c. Crop management factor: -

1. **Tillage** : - Zero/min. tillage – imparts resistance
2. **Monoculture** : - Selective influence of particular weed to grow & consequently – use of same herbicides to control- without rotation.

Management of herbicide resistance

Where resistance has already cropped up: -

1. Farmer's awareness, training & participatory approaches.
2. Abandonment of the herbicide to which weeds showing resistance.
3. Stopping of any sort of transaction of crop seed from an area having resistance to anew area.
4. Clean tillage & having equipment.
5. Rouging and prevention of seed production & contamination of crops at harvest.
6. Use of competitive - & high yielding variety smothering effect.
7. Use of pure & certified seed.
8. Stale seed bed technique – for *Phalaris minor*
   [fushes allowed to sprout – followed by killing up those flushes by non selective herbicide like Glyphosate @ 0.4 – 0.5 Kg a.i./ha]
9. Crop rotation/substitution: - It facilitates – herbicides rotation which is very effective.
10. Proper – residue management
11. Evaluation of alternative herbicide having different mode of action & using them in appropriate dose and time .
12. Herbicide mixture, sequence & rotation to avoid / delay development of cross / multiple resistances.
13. Herbicide rotation: - Once in every three years.
14. Use of herbicide resistance crops (HRCS) / GM crops / transgenics.

Herbicide resistant crops (HRC)

A. Alteration of a crop to provide resistance to a herbicide that normally would kill the crop

1. Traditional means of obtaining selectivity was to screen thousands of chemicals hoping to find a herbicide that could be used on a crop without causing injury
2. HRC involve screening genes for selectivity, rather than screening chemicals
3. As it has become more difficult to identify selective herbicides (easy ones already discovered), it is less expensive to screen genes

B. Methods of development

1. Traditional breeding techniques
    a. Triazine resistant canola – canola was crossed with a weedy mustard (field mustard) that had developed resistance to triazines following repeated use of atrazine (insensitive target site)
    b. ALS-resistant corn – created by mutagenesis of pollen by UV light. A mutation was found that resulted in an insensitive target site for ALS herbicides
2. Transgenic crops (genetic engineering)
    a. Gene that will provide resistance to a herbicide identified in some other organism and transferred to crop plant
    b. Glyphosate resistant (GR) crops (Roundup Ready)
        i. Most RR crops use a gene for an insensitive target site (EPSPS) found in bacterium. In some GR crops, a gene for an enzyme that metabolizes glyphosate is included along with the modified target site. A second gene for an insensitive enzyme has been identified from mutated corn is used in some GR crops.
        ii. Current RR crops: corn, soybean, cotton, sugarbeet, canola.
        iii. Numerous other crops developed, including wheat, creeping bentgrass, Kentucky bluegrass, etc. Registration is pending or on hold.
        iv. RR alfalfa was approved in 2006, but a court order in 2007 stopped planting of any new seed and established fields need to be closely monitored. Court decided that the movement of the RR gene into conventional alfalfa could cause loss of market for persons wanting to grow non-transgenic alfalfa
        v. A gene that codes for an enzyme that degrades glyphosate has been identified by DuPont and will be used in Optimum GAT crops. These crops will also contains a gene for resistance to ALS herbicides

c. Glufosinate resistant crops

i. Gene for an enzyme that degrades glufosinate identified in bacteria and inserted in crops

Current LL crops include corn, cotton, soybean and canola.

Chapter 13

Allelopathy

What Is Allelopathy?

Allelopathy refers to the beneficial or harmful effects of one plant on another plant, both crop and weed species, from the release of biochemicals, known as allelochemicals, from plant parts by leaching, root exudation, volatilization, residue decomposition, and other processes in both natural and agricultural systems. Allelochemicals are a subset of secondary metabolites not required for metabolism (growth and development) of the allelopathic organism. Allelochemicals with negative allelopathic effects are an important part of plant defense against herbivory (i.e., animals eating plants as their primary food) (Fraenkel 1959; Stamp 2003).

The term *allelopathy* is from the Greek-derived compounds *allelo* and *pathy* (meaning “mutual harm” or “suffering”) and was first used in 1937 by Austrian scientist Hans Molisch in the book *Der Einfluss einer Pflanze auf die andere - Allelopathie* (*The Effect of Plants on Each Other*) (Willis 2010). First widely studied in forestry systems, allelopathy can affect many aspects of plant ecology, including occurrence, growth, plant succession, the structure of plant communities, dominance, diversity, and plant productivity.

Nature of Allelopathy

Commonly cited effects of allelopathy include reduced seed germination and seedling growth. Like synthetic herbicides, there is no common mode of action or physiological target site for all allelochemicals. However, known sites of action for some allelochemicals include cell division, pollen germination, nutrient uptake, photosynthesis, and specific enzyme function. For example, one study that examined the effect of an allelochemical known in velvetbean, 3-(3’,4’-dihydroxyphenyl)-l-alanine (l-DOPA), indicated that the inhibition by this compound is due to adverse effects on amino acid metabolism and iron concentration equilibrium.

Allelopathic Chemicals

- Phenolic acids
- Coumarins- block mitosis in onion by forming multinucleate cells
- Terpinoids
- Flavinoids
- Scopulatens- inhibits photosynthesis without significant effect on respiration

Ways of releasing allelochemicals

Allelopathic chemicals are released from the plants as:

- Vapour- from roots and leaves from stomata
- Foliar lechate
- Root exudates
- Breakdown/decomposition product of dead plant parts
- Seed extract

1. **Volatilization:** Allelopathic tress release a chemical in a gas form through small openings in their leaves.
2. **Leaching:** Some plants store protective chemicals in their leaves. When the leaves fall n the ground, they decompose and give off chemicals that protect the plant. Water soluble phytotoxin may be leached from roots and above ground plant parts or they may be actively exuded from living roots. Rye and quack grass release allelopathic chemicals from rhizomes or cut leaves.
3. **Exudation:** Some plants release defensive chemicals into the soil through their roots. The released chemicals are absorbed by the roots of nearby trees. Exuding compounds are selectively to other plants. Exudates are usually phenolic compounds (e.g. coumarins) that tend to inhibit development.

Types of allelopathy

1. **Weeds on crop:**
   - *Agropyron repens* (Quack grass) generate ethylene in rhizomes due to microbial activity in soil, which interferes with uptake of nitrogen and potassium in maize and ultimately decrease in yield of it.
   - *Avena fatua* (Wild oat) residues inhibit germination of certain herbaceous species like wheat.
   - *Cynaodon dactylon* (Bermuda grass) residues remains in the field inhibits seed germination, root and top growth of barley.
   - *Sorghum halpense* (Jhonson grass) is a perennial weed in sugarcane, soybean, maize etc. Root exudates from decaying Jhonson grass is found to have inhibitory effect on these crops.
2. **Weed on weed:**
   - *Imperata cylindrica* (Cogon weed) inhibits the emergence and growth of annual broad leaf weed, i.e., *Borreria hispada* by exudation of inhibitory substance through rhizomes.

- *Sorghum halpense* (Jhonson grass)- living and decaying rhizomes inhibit the growth of *Setaria viridis* (Giant Foxtail), *Digitaria Sanguinalis* (Large carb grass) and *Amaranthus spinosus* (Spiny amaranth).

3. **Crop on weed:**
   - Oat, pea, wheat suppress the growth of *Chenopodium album* (Lambsquater).
   - *Coffea arabica* (Coffee) release 1,3,7 trimethylxanthin which inhibits germination of *Amaranthus spinosus* (Spiny amaranth).

Factors affecting allelopathic effect

1. **Varieties:** There can be great deal of difference in the strength of allelopathic effects between different crop varieties.
2. **Specificity:** The crop which shows strong allelopathic effect against one weed may show little or no effect against other weeds.
3. **Autotoxicity:** Sometimes plant species may also suppress the germination and growth of its own species. Eg. Lucerne
4. **Crops on crop effect:** Residues from allelopathic crops can hinder germination and growth of following crops as well as weeds.
5. **Environmental factors:** Low fertility increases allelopathic effects due to more production of allelochemiocals. Warm, wet condition can cause faster decline of allelopathic effect as against slowest decline under cold and wet condition.

Chapter 14

Growth and development of crops

Plant growth: It is the irreversible, quantitative increase in size, mass, and/or volume of a plant or its parts. It occurs with an expenditure of metabolic energy. Therefore, the events leading to leaf formation and the increase in height of a plant are growth, but the increase in volume of a seed due to uptake of water or imbibition is not growth. There are various ways of quantifying plant growth. These include cell number, fresh weight, dry weight, plant height, length, width, area, and volume. Each one has limitations. Growth is in general a combined effect of cell division and cell enlargement. But in some instances, growth can occur even without cell division and the reverse is also true. Likewise, early growth of the embryo in the flower can be quantified by the increase in cell number although these cells being small do not increase the size of the embryo.

Plant development: It is an overall term which refers to the various changes that occur in a plant during its life cycle. Development consists of both growth and differentiation involving quantitative and qualitative changes (Hopkins 1999). It is characterized by change in size, shape, form, degree of differentiation and state of complexity (Abellanosa and Pava 1987). However, there can be growth without differentiation and likewise there can be differentiation without growth.

Factors affecting growth and development

Plant growth factors control or influence plant characteristics as well as adaptation. In general, there are two factors affecting plant growth and development: genetic and environmental**.** The genetic factor is also called internal factor because the basis of plant expression (the gene) is located within the cell. The environmental factor is considered external, and refers to all factors, biotic and abiotic, other than the genetic factor. The genetic factor determines the character of a plant, but the extent in which this is expressed is influenced by the environment. The environmental factors are divided into two main groups: biotic and abiotic factors. The descriptive word biotic means living while abiotic means non-living or dead.

The climatic factors include rainfall and water, light, temperature, relative humidity, air, and wind. They are abiotic components, including topography and soil, of the environmental factors that influence plant growth and development.

Moisture:

In crop agriculture, water is an important climatic factor. It affects or determines plant growth and development. Its availability, or scarcity, can mean a successful harvest, or diminution in yield, or total failure. Most plants are mesophytes, that is, they are adapted to conditions with moderate supply of water. But some, called hydrophytes, require watery or water-logged habitats while others, called xerophytes, are more tolerant to dry conditions.

Light:

Light is a climatic factor that is essential in the production of chlorophyll and in photosynthesis, the process by which plants manufacture food in the form of sugar (carbohydrate).

Temperature:

The degree of hotness or coldness of a substance is called temperature. It is commonly expressed in degree Celsius or centigrade (C) and degree Fahrenheit (F). This climatic factor influences all plant growth processes such as photosynthesis, respiration, transpiration, breaking of seed dormancy, seed germination, protein synthesis, and translocation. At high temperatures the translocation of photosynthate is faster so that plants tend to mature earlier. In general, plants survive within a temperature range of 0 to 50 ^{0}C.

Air:

The oxygen and carbon dioxide in the air are of particular importance to the physiology of plants. Oxygen is essential in respiration for the production of energy that is utilized in various growth and development processes. Carbon dioxide is a raw material in photosynthesis. The favourable or optimal day and night temperature range for plant growth and maximum yields varies among relative humidity crop species.

Relative humidity:

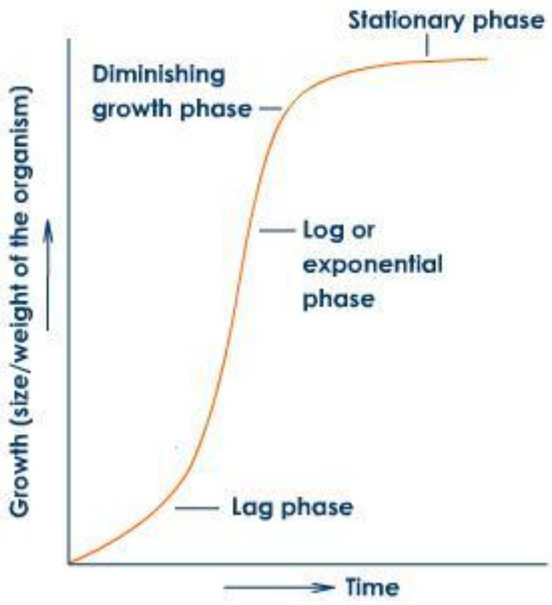
The relative humidity affects the opening and closing of the stomata which regulates loss of water from the plant through transpiration as well as photosynthesis. A substantial understanding of this climatic factor is likewise important in plant propagation. Newly collected plant cuttings and bare root seedlings are protected against desiccation by enclosing them in a sealed plastic bag. The propagation chamber and plastic tent are also commonly used in propagating stem and leaf cuttings to ensure a condition with high relative humidity.

Wind:

Moderate winds favour gas exchanges, but strong winds can cause excessive water loss through transpiration as well as lodging or toppling of plants. When transpiration rate exceeds that of water absorption, partial or complete closure of the stomata may ensue which will restrict the diffusion of carbon dioxide into the leaves. As a result, there will be a decrease in the rate of photosynthesis, growth and yield.

Sigmoid Growth Curve

The curve can be shown appearing slowly along the line and stabilizing. During the initial stage, i.e., during the lag phase, the rate of plant growth is slow. Rate of growth then increases rapidly during the exponential phase. After some time the growth rate slowly decreases due to limitation of nutrients. This phase constitutes the stationary phase.



The curve obtained by plotting growth and time is called a growth curve. It is a typical sigmoid or S- shaped curve.

Parameters used in growth analysis:

Leaf Area Index (LAI)

Leaf area is important for photosynthesis. Its estimation indicates both assimilating area and growth. For crop production leaf area per unit land area is more important than leaf area of individual plant. Leaf area index is the ratio between one sided leaf area to ground area.

$$\mathbf{LAI} = \frac{\textbf{Total leaf area for a given land area}}{\textbf{Land area considered}}$$

Crop growth rate (CGR):

It indicates at what rate the crop is growing i.e. whether the crop is growing at a faster rate slower rate than normal. It is expressed as g of dry matter produced per day.

$$\mathbf{CGR} = \frac{\mathbf{W_2 - W_1}}{\mathbf{T_2 - T_1}}$$

Where, W2 and W1 are the final and initial dry weights at times t2 and t1 respectively. It is expressed in g/m^2/day.

Relative growth rate (RGR):

This parameter indicates rate of growth per unit dry matter. It is similar to compound interest, wherein interest is also added to the principal to calculate interest. It is expressed as g of dry matter produced by a g of existing dry matter in a day.

$$RGR = \frac{Log_e W_2 - Log_e W_1}{L_2 - L_1}$$

It is expressed in g/g/day

Net Assimilation rate (NAR):

It indirectly indicates the rate of net photosynthesis. It is expressed as g of dry matter produced per dm2 of leaf area in a day. For calculating NAR, leaf area of individual plants has to be used but not leaf area index.

$$\mathbf{NAR\ (g\ m^{-2}\ day^{-1})} = \frac{\mathbf{(W_2 - W_1)(Log_e L_2 - Log_e L_1)}}{\mathbf{(T_2 - T_1)\ (L_2 - L_1)}}$$

Leaf Area Duration (LAD):

Yield of dry matter is a function of leaf area, net assimilation rate and duration of leaf area. Leaf area duration of a crop is a measure of its ability to produce leaf area on unit area of land throughout its life cycle.

$$LAD = \frac{L_2 - L_1}{Log_e L_2 - Log_e L_1} \times (t_2 - t_1)$$

It is expressed in days.

Chapter 15

Plant Ideotype

According to Donald, **ideotype** is a biological model which is expected to perform or behave in a particular manner within a **defined** environment: "a crop **ideotype** is a **plant** model, which is expected to yield a greater quantity or quality of grain, oil or other useful product when developed as a cultivar.

Features of Crop Ideotype:

The crop Ideotype consists of several morphological and physiological traits which contribute for enhanced yield or higher yield than currently prevalent crop cultivars. The morphological and physiological features of crop Ideotype is required for irrigated cultivation or rainfed cultivation. Ideal plant whether the Ideotype is required for irrigated cultivation or rainfed cultivation. Ideal plant types or model plants have been discussed in several crops like wheat, rice, maize, barley, cotton, and bean. The important features of Ideotype for some crops are briefly described below:

Wheat:

The term Ideotype was coined by Donald in 1968 working on wheat. He proposed Ideotype of wheat with following main features:

1. A short strong stem. It imparts lodging resistance and reduces the losses due to lodging.
2. Erect leaves. Such leaves provide better arrangement for proper light distribution resulting in high photosynthesis or CO_2 fixation.
3. Few small leaves. Leaves are the important sites of photosynthesis, respiration, and transpiration. Few and small reduce water loss due to transpiration.
4. Larger ear. It will produce more grains per ear.
5. A presence of owns. Awns contribute towards photosynthesis.
6. Presence of awns. Awns contribute towards photosynthesis.
7. A single culm.

Thus, Donald included only morphological traits in the Ideotype. However, all the traits were based on physiological consideration. Finally (1968) doubted the utility of single clum in wheat Ideotype. Considered tillering as important features of wheat flag type a wheat plant with moderately short but broad flag leaf, long flag leaf sheath, short ear extrusion with long ear, and moderately high tillering capacity should give yield per plant (Hsu and Watson, 1917). Asana proposed wheat Ideotype for rainfed cultivation. Recent workers included both morphological and physiological characters in wheat Ideotype.

Rice:

The concept of plant type was introduced in rice breeding by Jennings in 1964, through the term Ideotype was coined by Donald in 1968. He suggested that the rice an ideal or model plant type consists of 1) Semi dwarf stature. 2) High tillering capacity, and 3) Short, erect, thick and highly angled leaves (Jennings, 1964, Beachell and Jennings, 1965). Jennings also included morphological traits in his model. Now emphasis is also given to physiological traits in the development of rice Ideotype.

Maize:

In 1975, Mock and Pearce proposed ideal plant type of maize. In Maize , higher yields were obtained from the plants consisting of 1) Low tillers, 2) Large cobs, and 3) Angled leaves for good light interception. Planting of such type at closer spacings resulted in higher yields.

Barley:

Rasmusson (1987) reviewed the work on Ideotype breeding and also suggested ideal plant type of six rowed barley. He proposed that in barley, higher yield can be obtained from a combination of 1) Short stature, 2) Long awns, 3) High harvest index, and 4) High biomass. Kernel weight and kernel number were found rewarding in increasing yield

Cotton:

In cotton, genotypes with zero branch, short stature, compact plant, small leaves and fewer sympodia were considered to enhance yield levels. Singh et al. (1974) proposed and ideal plant type of uplant cotton growing belt. The proposed Ideotype includes

1) Short stature (90-120 cm),
2) Compact and sympodial plant habit making pyramidal shape,
3) Determinate the fruiting habit with unimodal distribution of bolling,
4) Short duration (150-165 days),
5) Responsive to high fertilizer dose,
6) High degree of inter plant competitive ability,
7) High degree of resistance to insect pests and diseases, and
8) High physiological efficiency, Singh and Narayana (1993) proposed an Ideotype of above two species for rainfed conditions. The main features of proposed Ideotype include, earliness (150-165 days), fewer small and thick leaves, compact and short stature, interminate habit, spares hairness, medium to big boll size, synchronous bolling , high response to nutrients, and resistance to insect and diseases.

Sorghum and Pearl millet:

Improvement in plant type has been achieved in Sorghum and Pearl millet through the use of dwarfing genes. In these crop dwarf F1 hybrids have been developed which have made combine harvesting possible.

Genetic improvements have been achieved thorough modification of plant type in several crop species. New Ideotype have been proposed for majority of crop plants. Swaminathan (1972) has listed several desirable attributes of crop Ideotype with special reference to multiple cropping in the tropics and sub tropics. These features include:

1) Superior population performance,

2) High productivity per day,

3) High photosynthetic ability,

4) Low photo respiration,

5) Photo and thermo sensitivity,

6) High response to nutrients,

7) High productivity per unit of water,

8) Multiple resistances to insect and diseases

9) Better protein quantity and quality

10) Crop canopies that can retain and fix a maximum of CO_2, and

11) Suitability to mechanization

Chapter 16
Crop rotation and its principles

Crop Rotation

It refers to recurrent succession of crops on the same piece of land either in a year or over a longer period of time. It is a process of growing different crops in succession on a piece of land in a specific period of time, with an objective to get maximum profit from least investment without impairing the soil fertility.

Principles of Crop rotation:

1. It should be adaptable to the existing soil, climatic and economic factors.
2. The sequence of cropping adopted for any specific area should be based on proper land utilization. It should be so arranged in relation to the fields on the farm that the yields can be maintained and soil losses through erosion reduced to the minimum.
3. The rotation should contain a sufficient acreage of soil improving crops to maintain and also build up the OM content of the soil.
4. In areas where legumes can be successfully grown, the rotation should provide for a sufficient acreage of legumes to maintain the N supply of the soil.
5. The rotation should provide roughage and pasturage for the livestock kept on farm.
6. It should be so arranged as to help in the control of weeds, plant disease & insect-pests.
7. It should provide for the acreage of the most profitable cash crops adapted to the area.
8. The rotation should be arranged as to make for economy in production & labour utilization exhaustive (potato, sugarcane) followed by less exhaustive crops (oilseeds & pulses).
9. The crops with tap roots should be followed by those which have fibrous root system. This helps in proper & uniform use of nutrients from the soil & roots do not compete with each other for uptake of nutrients.
10. The selection of crops should be problem and need/demand base.
    a. According to need of people of the area & family.
    b. On slop lands alternate cropping of erosion promoting and erosion resisting crops should be adopted.
    c. Under dryland or limited irrigation, drought tolerant crops (Jowar, Bajra), in low lying & flood prone areas, water stagnation tolerant crops (Paddy, Jute) should be adopted.
    d. Crops should suit to the farmer's financial conditions, soil & climatic conditions.
    e. The crops of the same family should not be grown in succession because they act like alternate hosts for insect pests & disease pathogens and weeds associated with crops.
    f. An ideal crop rotations is one which provide maximum employment to the family & farm labour, the machines and equipments are efficiently used so all the agricultural operations are done timely.

Advantages of Crop Rotation: An ideal crop rotation has the following advantages:

1. There is an overall increase in the yield of crops due to maintenance of proper physical condition of the soil and its OM content.
2. Inclusion of crops having different feeding zones and different nutrient requirements help in maintaining a better balance of nutrients in the soil.
3. Diversification of crops reduces the risk of financial loss from unfavourable weather conditions and damage due to pests & diseases.
4. It facilitates more even distribution of labour.
5. There is regular flow of income over the year.
6. The incidence of weeds, pests and diseases is reduced and can be kept under control.
7. Proper choice of crops in rotation helps to prevent soil erosion.
8. It supplies various needs of farmer & his cattle.
9. Agricultural operations can be done timely for all the crops because of less competition. 'The supervisory work also becomes easier."
10. Proper utilization of all the resources and inputs could be made by following crop rotation:

Cropping System: It represents a cropping pattern (i.e. the proportion of area under various crops at a point of time in a unite area) used on a farm and their interaction with farm resources, other farm enterprises and available technology, which determine their makeup. It is defined, as the order in which the crops are cultivated on a piece of land over a fixed period or cropping system is the way in which different crops are grown. In the cropping systems, sometimes a number of crops are grown together or they are grown separately at short intervals in the same field.

Cropping pattern:

The yearly sequence and spatial management of crops and fallow on a given area is known as cropping pattern.

Cropping pattern	Cropping system
Crop rotation is practiced by majority of farmers in a given locality	Management of cropping pattern for maximum benefits from a given resource base in a given environment
Type and arrangement of crops in time and space.	Cropping pattern used on a farm and their interactions with farm resources, other farm enterprises and available technology which determine their makeup.
The yearly sequence and spatial management of crops and fallow on a given area is known as cropping pattern.	Pattern of crops taken up for a given piece of land or order in which the crops are grown on a piece of land over a fixed period, associated with soil management practices such as tillage, maturing and irrigation.
The proportion of area under different crops at a point of time in a unit area.	

Chapter 17

Harvesting and threshing of crops

Removal of entire plant or economic parts after maturity from the field is called harvesting. It includes the operation of cutting, picking, plucking or digging or a combination of these for removing the useful part or economic part from the plants/crops. The portion of the stem that is left in the field after harvest is called as stubble. The economic product may be grain, seed, leaf, root or entire plant.

Harvest Index (H.I): It is the ratio of the economic yield to the total biological yield expressed as percentage. H.I = (Economic yield/Biological yield) × 100

Time of Harvesting: If the crop is harvested early, the produce contains high moisture and more immature ill filled and shriveled grains. High moisture leads to pest attack and reduction in germination percentage and impairs the grain quality. Late harvesting results in shattering of grains, germination even before harvesting during rainy season and breakage during processing.

External Symptoms of Physiological Maturity

The major symptoms of physiological maturity of some field crops are as follows:

• Wheat and Barely–Complete loss of green colour from the glumes.

• Maize and Sorghum–Black layer in the placental region of grain

• Pearl millet–Appearance of bleached peduncle

• Soybean–Loss of the green colour from leaves.

• Redgram–Green pods turning brown about 25 days after flowering.

Harvest Maturity Symptoms

The harvest maturity symptoms of some important crops are as follows:

• Rice–Hard and yellow coloured grains.

• Wheat–Yellowing of spikelets.

• Sorghum, Pearl millet, foxtail millet–Yellow coloured ears with hard grains.

• Ragi–Brown coloured ears with hard grains

• Pulses–Brown coloured pods with hard seeds inside the pods.

• Groundnut–Inner side of the pods turn dark from light color.

• Sugarcane–Leaves turn yellow.

• Tobacco–leaves slightly turn yellow in colour and specks appear on the leaves.

Criteria for Harvesting of Crops

The criteria for harvesting of crops are given in Table.

Crop	Criteria for Harvesting of Crops
Rice	32 days after flowering, Green grains not more than 4-9%
Wheat	About 15% moisture in grain, Grain in hard dough stage.
Maize	25–30 days after tasselling, Seed moisture content is at 34%
Sorghum	40 days after flowering
Cumbu	28–35 days after flowering
Redgram	35–40 days after flowering
Black/Green gram	Pod turn brown/black
Rapeseed/mustard	75% of the silique turn yellow, Seed moisture at 30%
Sunflower	Back of heads turns to lemon yellow
Groundnut	Yellowing of leaves and shedding Development of purple colour of the testa
Cotton	Bolls fully opened
Jute	50% pod stage (120–150 days)
Sugarcane	Brix 18–20%, Sucrose 15%

Determination of harvesting date is easier for determinate crops and difficult for indeterminate crops because at a given time, the indeterminate plants contain flowers, immature and mature pods or fruits. If the harvesting is delayed for the sake of immature pods, mature pods may shatter, if harvested earlier, yield is less due to several immature pods. This problem can be overcome by

• harvesting pods or ears when 75% of them are mature (or)

• periodical harvesting or picking of pods

• inducing uniform maturity by spraying Paraquat or 2, 4-D sodium salt.

In fodder crops, toxins present in the crop, nutritive value, purpose of harvest (whether for stall feeding or for storage) and single or multi cut are also to be considered during harvest. Example–HCN toxin content in sorghum is high up to 30–45 DAS.

Methods of Harvesting

Harvesting is done either manually or by mechanical means.

(*i*) **Manual:** Sickle is the important tool used for harvesting. The sickle has to be sharp, curved and serrated for efficient harvesting. Knife is used for harvesting of plants with thick and woody stems. Now-a-days improved type of sickle is available which reduce the drudgery of harvesting labourers.

(*ii*) **Mechanical:** Harvesting with the use of implements or machines.

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