LECTURE NO-7

TYPES OF TILLAGE – PREPATORY TILLAGE – FACTORS AFFECTING PREPARATORY CULTIVATION, AFTER CULTIVATION, PUDDLING

Tillage operations are grouped into two types based on the time at which they are carried out.

1. **Preparatory cultivation** – which is carried out before sowing the crop
2. **After cultivation** – That is practiced after sowing the crop.
   - → Primary tillage – Ploughing
   - → Secondary tillage – harrowing
   - → Seed bed preparation – country plough can be used.

Factors influencing preparatory tillage:

1. **The previous crop grown:** Stubble of previous crop influence the tillage (Redgram, cotton stubbles are very deep rooted and require deep tillage to remove them)
2. **The crop to be grown:** Crops like sorghum can be grown with rough tilth for very small seeded. Crops like tobacco, chilles etc fine tilth is required. Deep tillage is required for crops like tuber crops and sugarcane.
3. **Types of soil**: Clay soil can be ploughed only with in a narrow range of soil moisture and the power or drought required is high. Light textured soils can be ploughed under a wide range of soil moisture and require less drought.
4. **Climate:** Deep tillage is not permitted in shallow soils in low rainfall areas as it leads to rapid drying and loss of stored soil moisture.

   Deep cultivation is possible in high rainfall areas.
5. **Type of farming:** Intensive cropping requires intensive tillage.

Intercultivation:

Tillage operations done between the crop rows with the objectives of

- Destroying the weeds
- To form a soil mulch
- To prevent cracking of soil
- To prevent crust formation

Intercultivation starts from very early stage of crop i.e., two to three weeks from sowing. Short duration crops require two-three intercultivation while long duration crop require 3-4 weeks.

After cultivation:

It includes intercultivation and various other special operations carried out in a standing crop. They include.

1. Thinning and Gap filling.
2. Rogueing in crops for seed purpose.
3. Earthing up in crops, sugarcane, banana, and groundnut.
4. Cropping in banana
5. Desuckering oper in banana
6. Wrapping and propping in sugarcane
7. Nipping in castor
8. Topping, Trimming and desuk in tobaccor basal leaves are removed
9. Defoliation in cotton
10. Hand pollination in sunflower.

Fertilizer app in irrigation also comes under after cultivation.

PUDDLING

Rice growth and yield are higher when grown under submerged conditions. Maintaining standing water throughout the crop period is not possible without puddling. Puddling is ploughing the land with standing water so as to create an impervous layer below the surface to reduce deep percolation losses of water to provide soft seedbed for planting rice.

Puddling operation consists of ploughing repeatedly in standing water until the soil becomes soft and muddy. Initially, 5cm to 10 cm of water is applied depending on the water status of the soil to bring it to saturation and above and the first ploughing is carried out.

After 3 to 4 days, another 5 cm of water is applied and later after 2 to 3 days second ploughing is carried out. By this operation, most of the clods are crushed and majority of the weeds are incorporated. Within 3 to 4 days, another 5 cm of water is given and third ploughing is done in both the directions. The third ploughing can be done either with a wetland plough or with a wetland puddler. Planking or levelling board is run to level the field. To know whether puddling is thorough or not, a handful of mud is taken into the hand and pressed. If it flows freely through fingers and if there are no hard lumps, puddling is considered to be thorough. Unlike in other tillage operations, puddling aims at destroying soil structure. The individual soil particles viz., sand, silt and clay are separated during puddling operation. The soil layer with high moisture below the plough sole is compacted due to the weight of the plough. The soil particles separated during puddling settle later. The sand particles reach the bottom, over which silt particles settle and finally clay particles fill the pores thus making impervious layer over the compacted soil.

Puddling is done with several implements depending on the availability of equipment and nature of the land. Soils with bulk density less than 1.0 are considered as problem soils as puddling with animal-drawn implements is difficult. The feet of the animals sink very deep during puddling. Under such a situation, puddling is done with spades by manual labour. Most of the farmers use wetland plough or worn out dryland plough or mouldboard plough. Wetland puddler consists of a series of blades attached to a beam at an angle. When it is worked, the soil is churned and puddling operation is completed quickly compared to the country plough. Generally green manure is applied to rice field which is incorporated by green manure trampler. Tractor drawn implements can be used for puddling by attaching cage wheels to prevent sinking.

LECTURE NO-8

SOWING

Prerequisites for sowing:

1. Good tilth
2. Optimum soil moisture at sowing depth
3. Manures and fertilizers

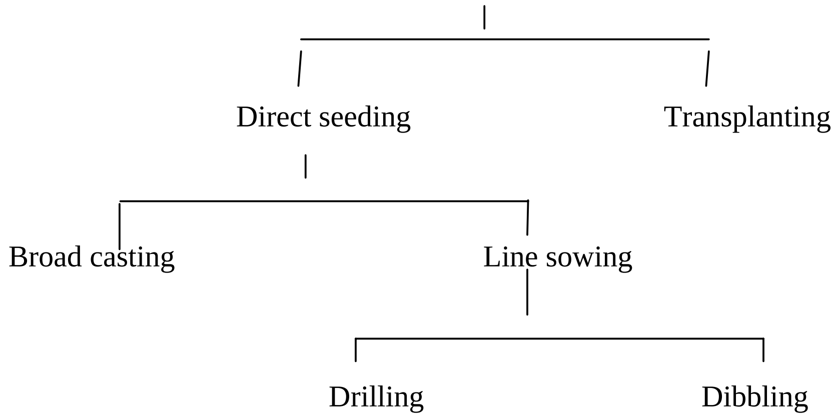
Seed material:

1. Seeds (grains used for sowing)
2. Veg propagules (stem cutling's rooted slips, tubers, rhizomes, etc)
   Stem cutlings – sugarcane, rose
   Rooted slips – forage crops. (Fodder crops)
   Tubers – potato
   Rhizomes – turmeric

Characteristics of seed or seed material:

1. **Purity:**
   Free from rogues (offtypes)
   Free from other crop seeds
   Free from weed seed.
   Free from inert material
2. Fully matured and well developed.
3. Free from storage pests and seed born diseases
   Ex. Red rot in sugarcane
   Tikka leaf spot in groundnut
4. Free from dormancy (dor. prob are seen in groundnut, rice, sunflower)
5. Viable (soybean looses viability quickly)
6. High percentage of germination (98-99%)
   (germi. Percentage in many grasses is 20-25%)

METHODS OF SOWING



Time of sowing:

1. Sowing very early in the season may not be advantageous.

   Eg: sowing rainfed ground nut early may result in failure of crop if there is prolonged dry spell from the 2nd week of june to 2nd week of july.
2. Delayed sowing invariably reduces yields

a. Eg: rainfed sorghum yields are reduced due to delay in sowing beyond June reason – sorghum sown late is subjected to severe atlack of shoot borer.

b. Eg: In rainfed groundnut sowing beyond July reduced the yields of all varieties at tirupathi.

3. Advancing sowing of Rabi sorghum. From November-September to October. Increase the yields considerably as more moisture would be available for early sown crop.
4. Sowing the crop at optimum time.

Increases yields due to suitable environment at all the growth stages of the crop.

1. Optimum time of sowing for Kharif crop – June or July
2. Optimum time for Rabi crop - last week of October to first week of November
3. Summer crop - First fortnight of January.

Depth of Sowing:

Uneven depth of sowing results in uneven crop stand.

- Plants will be of different sizes and ages and finally harvesting is a problem as there is uniformity in maturity.
- The thumb rule is to sow seeds to a depth approximately 3-4 times their diameter.

- The optimum depth of sowing for most of field crops ranges between 3-5 cm
- Shallow depth of sowing of 3-5 cm is enough for small seeds like sesamum finger millet and pearl millet.
- Very small seeds like tobacco are placed at a depth of ICM. Bold seeded crops like castor, groundnut, cotton, and maize etc. 6-7 cm.

Seed rate:

1.	Tobacco	-	30g per hector
2.	Mustard	-	2-3 Kg/ha
3.	Pulses	-	10-12Kg/ha
4.	Soybean	-	80-100 Kg/ha
5.	Groundnut	-	100-120 Kg/ha
6.	Forage grasses (rooted slips)	-	2-3 tons/ha
7.	Potato tubers	-	5-7 tons/ha
8.	Sugarcane (selts)	-	7 tons/ha

LECTURE NO – 9

CROP STAND ESTABLISHMENT – FACTORS AFFECTING OPTIMUM STAND ESTABLISHMENT

It is influenced by various Factors:

1. Quality of seed – purity, germination percent viability, free from dormancy, free from seed borne diseases, etc
2. Seed treatment:
    a. Fungicidal treatment – mainly to avoid seed borne and also soil borne diseases –Thiram, Captan, Mancozeb, Carbendazim, etc. used as per recommendations.
    b. Pesticide treatment – Malathian for control of scale insects in sugarcane, Quinolphos for stem borer of rice.
    c. Hot water treatment – 52^0C for 30 minutes to control red rot and smut diseases in sugarcane.
    d. Special treatments – dung treatment or acid treatment (100 ml conc. H_2SO_4/kg seed) of cotton for removing fuzz (for sowing by using seed drills, so that the seeds do not cling to each other in the seed tube)
    e. Scarification **–** Rubbing against hard surface to soften the hard seed coat (e.g: castor) or to remove the glumes covering the seed (eg: stylo) or soaking in water for 12-24 hrs. (Eg: rice, stylo) splitting the seeds into locules (e.g.: coriander) or compound bulbs into individual cloves – (e.g: garlic).
    f. Breaking dormancy – GA., cytokinins, Ethelene (500ppm for 12hrs)
    g. Mixing seed with other materials to increase the bulk in case of small seeded crops, mixing with sand or soil in case of crops like Sesamum, Lucerne, mustard, ragi, etc.
    h. Removal of broken kernels, ill filled seed – eg: Groundnut.
    i. Rhizobium treatment – in case of legumes – specific Rhizobium cultures are available depending upon the crop. These are helpful in fixing atmospheric – N. use 125g. jaggery in 1 litre of water – boil – cool – add Rhizobium culture (500g) and then thoroughly mix with seed (for 1 hour) and shade dry before sowing (R.japonicum, R.melitotus. are some examples)
3. Seed bed preparation

    Coarse tilth for groundnut, redgram, etc

    Fine tilth for ragi, mustard, etc
4. Time of sowing – important to meet the climatic requirements of each crop.

    This is very important in rain fed crops. In case of late sowing (maturity may coincide with drought), pest and disease incidence may be more and may affect the crop stand (eg: stem borer in sorghum) kharif crops – June – July (best time for sowing) rabi crops – October.

5. Depth of sowing – related to seed size, soil moisture availability, deep sowing may result in poor crop stand (low germination). Too shallow, sowing may also result in failure of germination.
6. Optimum soil moisture
7. Optimum soil temperature and aeration
8. Spacing – depends on crop and variety
9. Proper covering of the seed – in broadcast sowing bird damage is more if seeds are not properly covered.
10. Formation of soil crust – in case of lateritic soils soil crust formation may hinder germination. Shallow and frequent harrowings are practiced to break the crust. (blind hoeing)
11. Compaction of seed bed – firm compaction is required between seed and soil for good germination and also to minimize soil moisture loss. But hard compaction may prevent seedling emergence. This may happen in heavy soils.
12. Bird damage in some crops – crops dig the soil and carry away sprouted seeds of maize. (also in sunflower)

LECTURE NO-10

PLANTING GEOMETRY – COMPETITION – TYPES OF COMPETITION, INTRA AND INTER PLANT COMPETITION – PLANT POPULATION – EFFECT OF PLANT POPULATION ON GROWTH AND YIELD – OPTIMUM PLANT DENSITY AND PLANTING PATTERN

Competition – types of competition, plant population, intra and inter plant growth and yield, optimum plant density and planting pattern.

What is competition?

Competition is the struggle between individuals with in a population for available resources, when the level of resources is below the combined need of the members of the population.

How does competition occur in plants?

Crop plants are not grown in isolation but in closely spaced populations. In the early phase of growth, individual plants are small and widely spaced and do not interfere with each other. At some point, as the plants grow, they start to interfere with their neighbours and competition begins. Two plants, no matter how close, do not compete with each other so long as the growth resources are in excess of the needs of both. When the immediate supply of a single necessary factor falls below the combined demand of the two plants, competition begins.

TYPES OF COMPETITION

1. **Competition for nutrients:** Nutrient uptake increase with increase plant population. Higher population under low fertility conditions leads to development of nutrient deficiency symptoms because of competition.
2. **Competition for light:** Competition for light may occur whenever one plant casts a shadow on another or within a plant when one leaf shades another leaf. In early plant growth stages, there will be little mutual shading and even at relatively low light intensities the plant will be able to photosynthesize with full efficiency. As the plants develop, mutual shading increase and light becomes a limiting factor.
3. **Competition for water:** The success of any plant in community for water depends on the rate and competitiveness with which it can make use of the soil water supply.
4. **Intra-specific and inter-specific competition:** In populations of similar genotypes, in the absence of weeds, the competition is intra-specific (with in species), where different species of crops are growth, in mixtures and where weeds present, the competition is inter-specific (between species).

Plant population and growth

- High plant density brings out certain modifications in the growth of plants.
- Plant height increases with increase in plant population due to competition for light.
- Sometimes it may happen that moderate increase in plant population may not increase but decrease plant height due to competition for water and nutrients but not for light.
- Leaf orientation is also altered due to population pressure. The leaves are erect narrow and are arranged at longer vertical intervals under high plant densities. This is a desirable architecture.

Plant population and yield

- Decrease in yield of individual plant at high plant density is due to the reduction in the no. or earls or panicles.
- Ex: - Redgram produces about 20 pods per plant at 3.33 lakh plants/ha (30x10cm) while it produces more than 100 pods per plant at 50,000 plants/ha (80x25cm).
- Under very high population levels plant become barren, hence optimum plant population is necessary to obtain maximum yield.

Optimum plant population

Optimum plant population for any crop varies considerably due to environment under which it is grown. It is not possible to recommend a generalized plant population since the crop is grown in different seasons with different management practices.

E.g.:- Redgram plants sown as winter crop will have half the size of those grown in monsoon season. Optimum plant population is 55,000 plants/ha. For monsoon season crop of redgram and this is increased to 3.33 lakh plants/ha for winter crop; as low temperature retards the rate of growth, higher population is established for quicker ground cover.

In sorghum, when the climate is favourable during pre-anthesis period, the optimum population is two lakh plants/ha and when it is not congenid for growth during pre-anthesis, it is four lakh plants/ha.

PLANTING PATTERN

Planting pattern influences crop yield through its influence on light interception, rooting pattern and moisture extraction pattern. Different planting patterns are followed to suit different weed control practices and cropping systems. Plant geometry refers to the shape of plant while crop geometry refers to the shape of space available for individual plants. Crop geometry is altered by changing inter and intra-row spacing.

Square planting

It is reasonable to expect that squares arrangement of plants will be more efficient in the utilization of light, water and nutrients available to the individuals than in a rectangular arrangement. In wheat, decreasing inter-row spacing below the standard 15-12 cm i.e., reducing rectangularity, generally increases yield slightly. In crops like Tobacco, intercultivation in both directions is possible in square planting and helps in effective control of weeds. However, square planting is not advantageous in all crops. Groundnut sown with a spacing of 30x10cm (3.33 lakh/ha) gave higher pod yield than with same amount of population in square planting. Pod yield is reduced either by increasing rectangularity or approaching towards square planting.

Rectangular planting

Sowing the crop with seed drill is the standard practice. Wider inter-row spacing and closer intra-row spacing is very common for most of the crops, thus attaining rectangularity. This rectangular arrangement is adopted mainly to facilitate intercultivation. Sometimes only inter-row spacing is maintained and intra-row spacing is not followed strictly and seeds are sown closely as solid rows.

Miscellaneous planting arrangements

Crops are sown with seed drills in two directions to accommodate more number of plants and mainly to reduce weed population. Crops like rice, finger millet are transplanted at the rate of 2-3 seedlings per hill. Transplanting is done either in rows or randomly. Skipping of every alternate row is skipped, and the population is adjusted by decreasing intra-row spacing, it is known as paired row planting. It is generally restored to introduce an intercrop.

LECTURE NO - 13

IRRIGATION MANAGEMENT – IMPORTANCE OF IRRIGATION – OBJECTIVES OF IRRIGATION – DRAINAGE AND ITS ADVANTAGES

IRRIGATION:

Irrigation is the artificial application of water to the soil to supplement the rainfall and groundwater contribution to assist the crop production.

Objectives /Importance of Irrigation

1. To supply the moisture essential for plant growth.
2. For better utilization of production factors. (nutrients)
3. To provide crop insurance against short spells of drought.
4. To dilute/washout soluble salts
5. To soften tillage pans
6. Intensive cropping is made possible
7. Timely seedbed preparation and timely sowing.
8. To create favorable microclimate for crop growth.
9. Higher yields as well as stability in production

Method of irrigation

Depending on soil type slope source of irrigation water, nature of crop methods differs.

1. Surface methods of irrigation
   a. Flooding
   b. Boarder strip
   c. Corrugations
   d. Check basin
   e. Ridge and furrow
   f. Ring or basin
2. Sub- surface methods
3. Sprinkler – system.
4. Drip/trickle irrigation.
5. Quantity of irrigation water depends on rooting depth and water holding capacity of soil.
6. Irrigation water can be quantified through weirs, flumes, orifices, water meters etc.

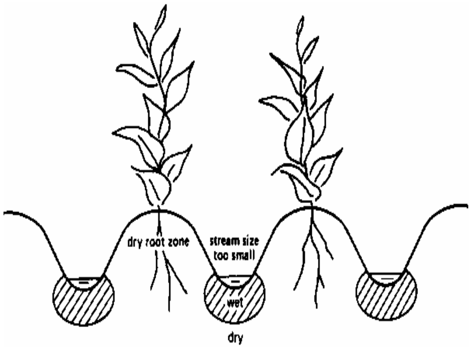


Fig: 13.1 Ridge and Furrow method

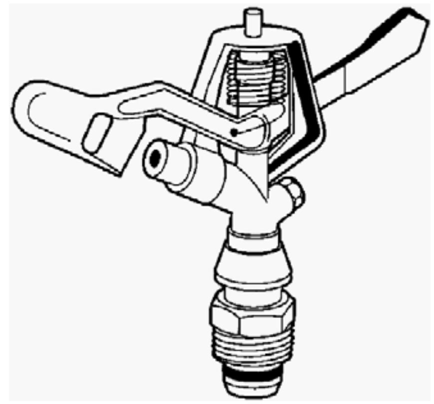


Fig:13.2 Sprinkler Nozzle

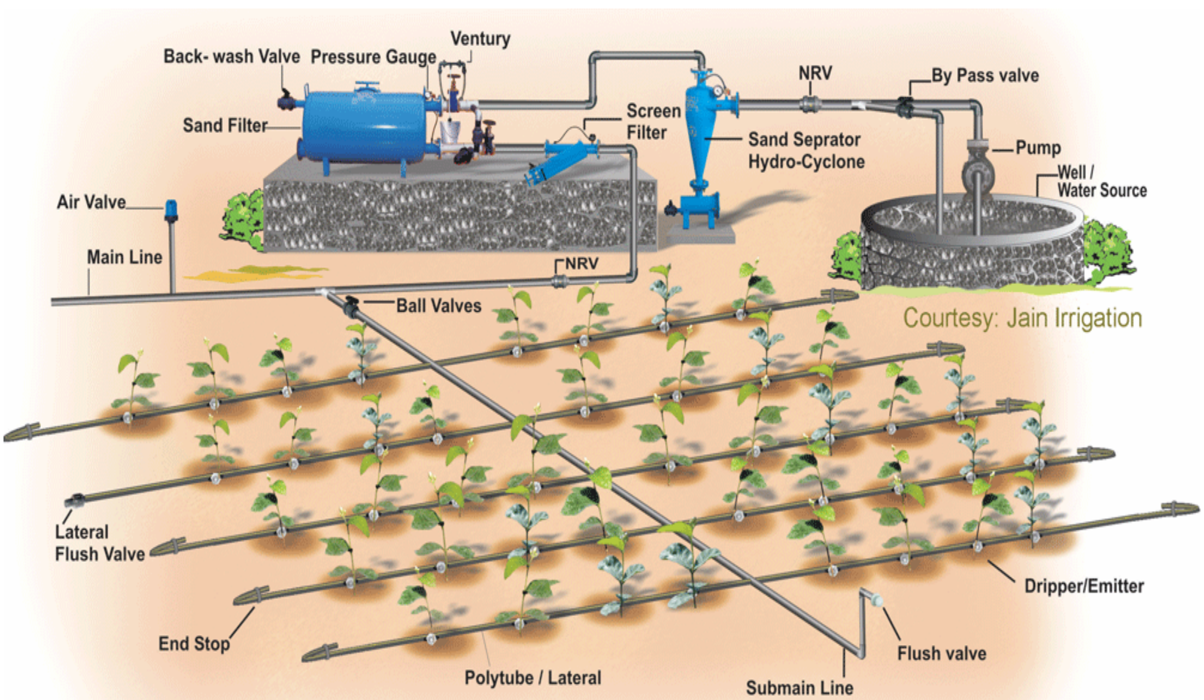


Fig:13.3 Drip Irrigation System

Drainage: Removal of excess water from the surface or below the surface of the soil so as to create favourable conditions for plant growth.

Causes of Water Logging

1. Intensive rains
2. Floods
3. Soil slope
4. Bunds
5. Defective irrigation
6. Seepage from unlined canals.

Effects of ill drained conditions

1. Lack of accretion of soil.
2. Restricted root growth and lodging problems
3. Difficulty in tillage.
    1. Increase in salinity in top layers of soil.

       All crops including rice require well drained conditions. Crops like maize mustard are very sensitive to water logging or ill drainage even for a short period. Mid season drainage is important in rice.
    2. Drainage can be surface drainage (or) Sub surface drainage.

Benefits of drainage

1. Helps in soil ventilation/acration
2. Facilitates timely tillage operations.
3. Better and healthy root growth.
4. Favours growth of soil microorganism (better mineralization)
5. Warming up for optimum soil temperature maintenance.
6. Promotes leaching and reduce logging.
7. Improves anchorage and reduce lodging.
8. Improves soil structure and decrease soil erosion.
9. Improves sanitary and health conditions and makes rural life happy.

LECTURE NO - 14

CROPPING SYSTEMS – MONOCROPPING – DEFINITION AND PRINCIPLES OF CROP ROTATION – MIXED CROPPING – INTERCROPPING – RELAY CROPPING – MULTISTORIED CROPPING – SOLE CROPPING – SOLE CROPPING AND SEQUENCE CROPPING

Cropping pattern: - It means the proportion of area under various crops, at a point of time in a unit area. It indicates the yearly sequence and spatial arrangement of crops and fallow in an area.

Decrease keeping the field vacant

Cropping System: It is an order in which the crops are cultivated on a piece of land over a fixed period this is cropping system.

Monocropping: or Monoculture refers to growing of only one crop on a piece of land year after year.

Ex: Rice – Rice (In Godavari belt)

Groundnut every year in Anantapur dist.

Disadvantage in Monocropping

- Improper use of moisture and nutrients from the soil
- Control of crop associated pests and weeds become a problem.

Crop rotation: It is a process of growing different crops in succession on a piece of land in a specific period of time with an object to get maximum profit from least investment without impairing soil fertility.

Principles of crop rotation:

1. The crops with tap roots should be fall by those which have a fibrous root system
2. The leguminous crops should be grown after non leguminous crops.
3. More exhaustive crops should be followed by less exhaustive crop.
4. Selection of crops should be demand based.
5. Selection of crops should be problem based.
6. The crops of the same family should not be grown in succession because the act like alternate hast for insects, pests and disease pathogens.

7. An ideal crop rotation is one which provides maximum employment to the family and farm labour, the machines and equipments are efficiently used then all the agriculture operations are done simultaneously.

Multiple cropping

Growing two or more crops on the same piece of land in one agriculture year is known as ‘***Multiple cropping’***.

It is the intensification of cropping in time and space dimensions i.e., more number of crops with in a year and more number of crops on the same piece of land.

It includes intercropping, mixed cropping and sequence cropping.

Inter Cropping: It is growing two or more crops simultaneously on the same piece of land with a definite row pattern.

Ex: Setaria + Redgram in 5:1 ratio

Groundnut + Redgram in 7:1 ratio

(a). Additive series

(b). Replacement series

Mixed cropping

It is the process of growing two or more crops together in the same piece of land. This system of cropping is generally practiced in areas where climatic hazards such as flood, drought, frost etc. are frequent and common.

Sequence cropping

It can be defined as growing of two or more crops in sequence on same piece of land in a farming year.

Depending on number of crops grown in an year. It is called double, triple and quadruple cropping involving two, three and four crops respectively.

Relay cropping: It is analogous to a relay race where crop hands over land to next crop in quick succession.

Ex: Maize – Early Potato – Wheat – Mungo

Overlapping system of cropping:

In this the succeeding crop is sown in standing proceeding crop thus in this system before harvesting one crop the seeds of next crop are sown.

Ex: Maize potato onion bendi in North India.

Ratoon cropping: It refers to raising a crop with re growth coming out of roots or stalks after harvest of the crop.

Ex: Sugarcane.

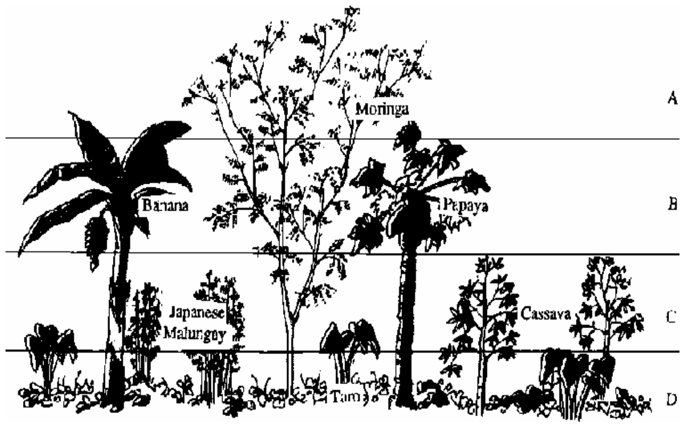


Fig:14.1 Multi Storeyed Cropping System

Multi Storeyed System: Growing of plants of different heights in same field at the same time is termed as multistoreyed cropping.

Ex: Coconut – Piper - banana – Pineapple.

Difference between intercropping and mixed cropping

S. No	Intercropping		Mixed cropping
1.	The main objective is to utilize the space left between two rows of main crop especially during early growth period of main crop.	1.	Main objective is to get at least one crop under any climatic hazards (flood, drought or frost) conditions.
2.	More emphasis is given to the main crop and subsidiary crops are not grown at the cost of main crop thus there is no competition between main and subsidiary crop.	2.	All crops are given equal care and there is no main or subsidiary crop. Almost all the crops compete with one another.
3.	Subsidiary crops are of short duration and they are harvested much earlier than main crop.	3.	The crops are almost of same duration.
4.	Both the crops are sown in rows. The sowing time may be the same or the main crop is sown earlier than subsidiary crop.	4.	Crops may be broad casted and sowing time for all the crops is the same.

24. **ABSCISSION AND SENESCENCE**

Like human beings, plants a1so grow old and undergo aging and then they die. *Aging is the sum total of changes in the total plant or its organs.* During aging, the plants undergo chemical and structural changes. Aging leads to senescence and later phase of development that u1timately terminates to death.

Senescence

The deteriorative process which naturally terminates the functional life of an organ, organism or other life unit is collectively called senescence. Senescence is a phase of the *aging process.* The major characteristic of senescence is that the metabolic processes are catabolic and eventually become irreversible and terminate to death.

Senescence is not confined only to whole plant. It may be limited to a particular plant organ such as leaf and flowers or cells or cell, organelles. Senescence is closely associated with the phenomenon of aging. Aging leads to senescence. Wheat plant dies after the development of fruit. This is the senescence of an entire plant. *Leaf fall* in a coconut tree is an example of senescence.

Types of senescence

Leopold (1961) has proposed types of senescence patterns in plants which are as follows.

(a) Overall Senescence

This type of senescence occurs in annuals where whole plant is affected. It is also called *whole plant senescence.* The entire plant dies after the development of fruit and seeds. E.g. Paddy, wheat, soybean etc.

(b) Top Senescence

In top senescence, the parts remaining above the ground or (shoot system) may die, but the root system and underground system remain viable. It is also called *shoot senescence.* E.g. Dock, perennial herbs.

(c) Deciduous Senescence

In deciduous woody plants, all the leaves die but the bulk of the stem and root system remains viable. It is called *deciduous senescence* or *simultaneous* or *synchronous senescence.* E.g. Leaf fall in deciduous trees.

(d) Progressive Senescence

It is a gradual death of old leaves from the base to the top of the plants. It may occur at any time. It is also called *sequential senescence.* E.g. Leaf fall in a coconut tree.

Causes of Senescence

1. Leaf senescence is accompanied by early loss in *chlorophyll,* RNA and enzymes.
2. Cellular constituents are decreased due to slower synthesis or faster break down.
3. Competition between vegetative and reproductive organs for nutrients.
4. A senescence factor (a hormone) is produced in soybean fruits that move to leaves where it causes senescence.
5. Short-day and long-night conditions induce flowering and leaf senescence.
6. Degradation of food reserves and loss of integrity in food storage cells of seeds.
7. Senescence is also hormonally controlled.

Physiology of Senescence

The following physiological changes occur during senescence.

1. *Photosynthesis* stops.
2. *Chlorophyll* degradation: The colour of leaf changes from green to yellow.
3. *Anthocyanin* pigments accumulation in the leaves causing reddening in leaves.
4. The vacuoles function as *lysosomes* and digest the cellular materials.
5. The starch content decreased.
6. RNA and proteins are decreased.
7. DNA molecules are degraded by the enzyme DNase.
8. Growth promoting hormones such as cytokinin decrease.
9. The deteriorative hormones such as *ethylene* and *abscisic acid* (ABA) content are increased.

Senescence Promoters

Senescence is promoted by hormones such as abscisic acid and ethylene. The senescence accelerating ability of abscisic acid is well documented. The function of *ABA as a promoter of flower tissue senescence including initiaton of colour fading or blueing has been established.* The ABA content of aging leaves increases markedly as senescence is initiated. *Ethylene* plays a very important role in the senescence of certain plant parts, particularly fruit and petals and in the abscission process. It is an inducer in the senescence of flower tissue. Senescence Retardants: The primary plant hormones involved here are auxin, gibberellin and cytokinin.

Significance of Senescence

1. The whole plant senescence occurs in monocarpic plants coinciding the seed setting and seed dispersal.
2. Due to the formation of abscission layer, the older leaves tend to fall down so that the nutrients will be diverted to the next young leaf.
3. The senescence process helps the mobilization of nutrients and of the vegetative parts of the plant into the fruits.
4. Plants escape the influence of seasonal adversity by undergoing senescence of its organs. Leaf fall in deciduous trees reduces the rate of transpiration to survive under adverse conditions.

Abscission

Shedding of leaves, flowers and fruits is called abscission. Abscission is distinct in deciduous trees and shrubs. In autumn, all the leaves of deciduous plants fall, at about the same time giving the plants a naked appearance. In evergreen plants there is gradual abscission of leaves. The older leaves fall while new leaves are developed continuously throughout the year. In most of the herbaceous species, however the leaves are not shed even after they die. In many cases leaves are retained in withered dry condition even after the whole shoot is dead.

Abscission is a complex physiological process. During abscission, the colour of the leaves, flowers and fruits changes due to degradation of chlorophyll and the synthesis of *anthocyanin* pigment.

Leaf abscission takes place at the base of the petiole. The site of abscission is internally marked by a distinct zone called *abscission zone.* This zone is made up of one or more layers of cells arranged transversely across the petiole base. This is called *abscission layer.* The abscission zone is pale or brown in colour. The cells of the abscission layer separate from each other due to the dissolution of middle lamellae and the primary cellulose walls under the influence of the activity of enzymes, *pectinase* and *cellulase.*

At this stage, the petiole remains attached to the stem by vascular elements only. But due to its own weight and the wind force, the leaf is detached from the stem. The broken vascular elements are soon plugged with *tyloses* or gums. Wound healing in cells proximal to the breaking point involves formation of a corky layer that protects the plant from pathogen invasion and excess water loss. *Suberin* and *lignin* are synthesized during healing.

Several environmental factors such as drought and N deficiency promote abscission. *Auxin* is synthesized in growing leaf blades and it strongly retards senescence and abscission. Abscission starts when the amount of auxin begins to decrease. Cytokinins and gibberellins arriving from the roots also delay senescence and abscission. Abscission is caused by the formation of cell wall degrading enzymes in the abscission zone, due to ethylene production.

Significance of Abscission

1. It helps in diverting water and nutrients to the young leaves
2. It is a self pruning process through which fruits and injured organs are shed from the parent plant.
3. It helps in disseminating fruits and vegetative propagates.
4. Abscission serves as function in removing plant parts containing waste materials.

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Review

Seed priming in field crops: potential benefits, adoption and challenges

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Abstract. Seed priming is a presowing technique in which seeds are moderately hydrated to the point where pregermination metabolic processes begin without actual germination. Seeds are then redried to near their actual weight for normal handling. Seeds can be soaked in tap water (hydropriming), aerated low-water potential solutions of polyethylene glycol or salt solutions (KNO_3, KH_2PO_4, KCl, NaCl, $CaCl_2$ or $MgSO_4$; osmopriming), plant growth regulators, polyamines (hormonal priming), plant growth-promoting bacteria (biopriming), macro or micronutrients (nutripriming) or some plant-based natural extracts. Here, we review: (1) seed priming as a simple and effective approach for improving stand establishment, economic yields and tolerance to biotic and abiotic stresses in various crops by inducing a series of biochemical, physiological, molecular and subcellular changes in plants; (2) the tendency for seed priming to reduce the longevity of high-vigour seeds and improve the longevity of low-vigour seeds; (3) the advantages of physical methods of seed priming to enhance plant production over conventional methods based on the application of different chemical substances; (4) the various physical methods (e.g. magneto-priming and ionising radiation, including gamma rays, ultraviolet (UV) rays (UVA, UVC) and X-rays) available that are the most promising presowing seed treatments to improve crop productivity under stressful conditions; and (5) effective seed priming techniques for micronutrient delivery at planting in field crops. Seed priming as a cost-effective approach is being used for different crops and in different countries to improve yield, as a complementary strategy to grain biofortification and in genetically improved crop varieties to enhance their performance under stress conditions, including submergence and low phosphorus. Some of the challenges to the broad commercial adaption of seed priming include longevity of seeds after conventional types of priming under ambient storage conditions and a lack of studies on hermetic packaging materials for extended storage.

Additional keywords: abiotic stresses, economic benefits, grain fortification, non-invasive priming, seed longevity, subcellular basis.

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Introduction

Rapid human population growth, high food prices and fast dietary transitions are threatening agricultural production systems. Further, inadequate production practices threaten food security and contribute to the depletion and degradation of natural resources, which creates political and economic instability (Beddington *et al*. 2012). Moreover, the changing climate increases the severity of the problem and alters crop production levels needed to meet the energy requirements of future generations (Fedoroff *et al*. 2010). Poor seedling emergence and inadequate stand establishment are major constraints to crop productivity, but most farmers lack the resources for proper seedbed preparation and other crop production practices (Singh *et al*. 2015). Unfavourable soil moisture or lack of rainfall at sowing results in poor and unsynchronised seedling emergence (Angadi and Entz 2002), which reduces crop yields. Crop growth and productivity are governed by a range of abiotic and biotic factors, with optimum productivity ensured when both (abiotic and biotic) factors are within the optimum range. Abiotic stresses, including drought (Farooq *et al*. 2014, 2015*a*), waterlogging (Olgun *et al*. 2008), extreme temperatures (Farooq *et al*. 2011*a*), salinity (Munns and Tester 2008; Farooq et al. 2015*b*), phototoxic compounds (Jamal *et al*. 2006), low or high solar radiation (Alexieva *et al*. 2001) and insufficient soil mineral nutrients (Fageria *et al*. 2010), reduce yields by up to 50% (Bray *et al*. 2000), whereas biotic stresses, including animal and insect attack or damage, weeds and diseases, reduce crop potential.

Seed priming is an easy to apply, low-cost and effective method that can improve crop performance. It is primarily a hydration treatment that involves soaking seeds overnight with or without aeration (on-farm priming) or in solutions of low water potential, followed by drying to the original moisture level before sowing or being packed and stored until needed (Bradford 1986; Farooq *et al*. 2006*a*, 2006*b*). Better stand establishment and optimum plant populations are a major challenge for successful crop production (Chivasa *et al*. 1998; Fanadzo *et al*. 2010; Rehman *et al*. 2011*a*). Constraints to good establishment include late sowing, low seed quality (Finch-Savage and Bassel 2016), inadequate soil moisture (Antonino *et al*. 2000) and adverse environmental conditions (Farooq *et al*. 2009*a*, 2011*a*, 2014). Seed priming can result in better seedling emergence, uniform stand establishment, earlier flowering and, ultimately, better crop yields (Harris *et al*. 2007; Rehman *et al*. 2011*a*; Singh *et al*. 2015; Ullah *et al*. 2019*a*). Priming of wheat (*Triticum aestivum* L.) seeds with KCl and $CaCl_2$ enhanced seedling emergence and improved stand establishment, resulting in better crop performance due to a reduction in the time between seed sowing and seedling emergence and synchronisation of emergence (Fig. 1; Parera and Cantliffe 1994; Farooq *et al*. 2008*a*). Synchronised and uniform germination due to seed priming is attributed to a decline in the lag time to imbibition, enzyme activation, a build-up of germination-enhancing metabolites, repair of metabolic segments during imbibition and better osmotic adjustment (Bradford 1986; Lee and Kim 2000; Farooq *et al*. 2006*b*; Brocklehurst and Dearman 2008; Hussain *et al*. 2015; Ullah *et al*. 2019*a*). Moreover, seed priming induces tolerance to abiotic and biotic stresses (Harris *et al*. 2007) due to the accumulation of latent defence proteins and enhanced stress response (Borges *et al*. 2014). Seed priming strengthens the cellular defence response that enhances the tolerance mechanism against biotic and abiotic stresses in field crops (Jisha *et al*. 2013). Some promising reviews (e.g. Farooq *et al*. 2006*b*, 2006*c*, 2012) and books (e.g. Taiz *et al*. 2015) highlight priming techniques that enhance tolerance to abiotic stresses. Wahid and Farooq (2012) reviewed the economic benefits of seed priming, but no comprehensive review has covered all aspects of seed priming, including seed longevity. This is the first review to present the benefits of seed priming on a physiological, biochemical and subcellular basis, its types, its effects on the longevity of stored primed seeds and its role in grain biofortification to fulfil human micronutrient deficiencies. This review also covers the effects of stress (thermal, salt, drought and nutrient) on plant growth and development, and the use of seed priming treatments to reach optimum yields under stressed and non-stressed conditions.

Seed priming and its types

Seed priming is a presowing controlled hydration treatment that allows pregermination metabolism without actual germination; seeds are then redried to near their original weight for routine handling (Bradford 1986; Fig. 2). During priming, seeds are submerged in water (with or without aeration) or in a solution with low water potential. Various agents are used for seed

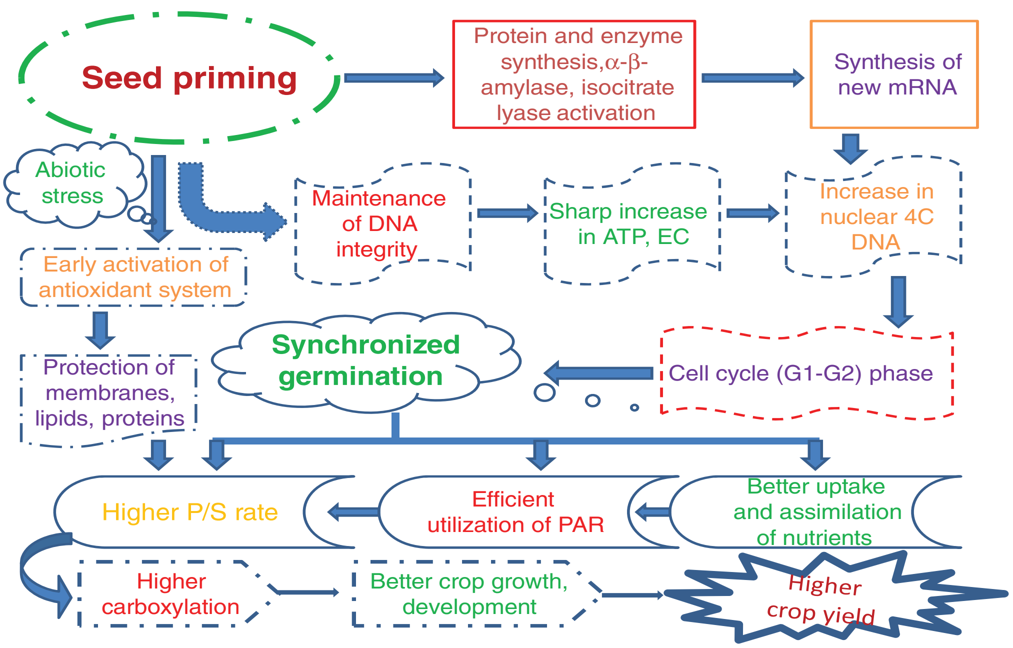

Fig. 1. Physiological and biochemical bases of seed priming-induced benefits. Seed priming initiates protein and enzyme synthesis, activates α- and β-amylase and isocitrate lyase, synthesises new mRNA, maintains DNA integrity, increases the energy charge and ATP content, and increases nuclear 4C DNA content, all of which result in cell cycle advancement from the G_1 to G_2 phase for synchronised germination. The photosynthetic (P/S) rate increases due to the efficient uptake and assimilation of nutrients and better utilisation of photosynthetically active radiation (PAR; Xu and Qiu 2007). Seed priming results in early activation of an antioxidant system that protects membranes, lipids and proteins under abiotic stresses, such as salinity and drought. The higher photosynthetic rate leads to higher carboxylation and better crop growth and development, which ultimately improves crop yield and harvest index. EC, electrical conductivity.

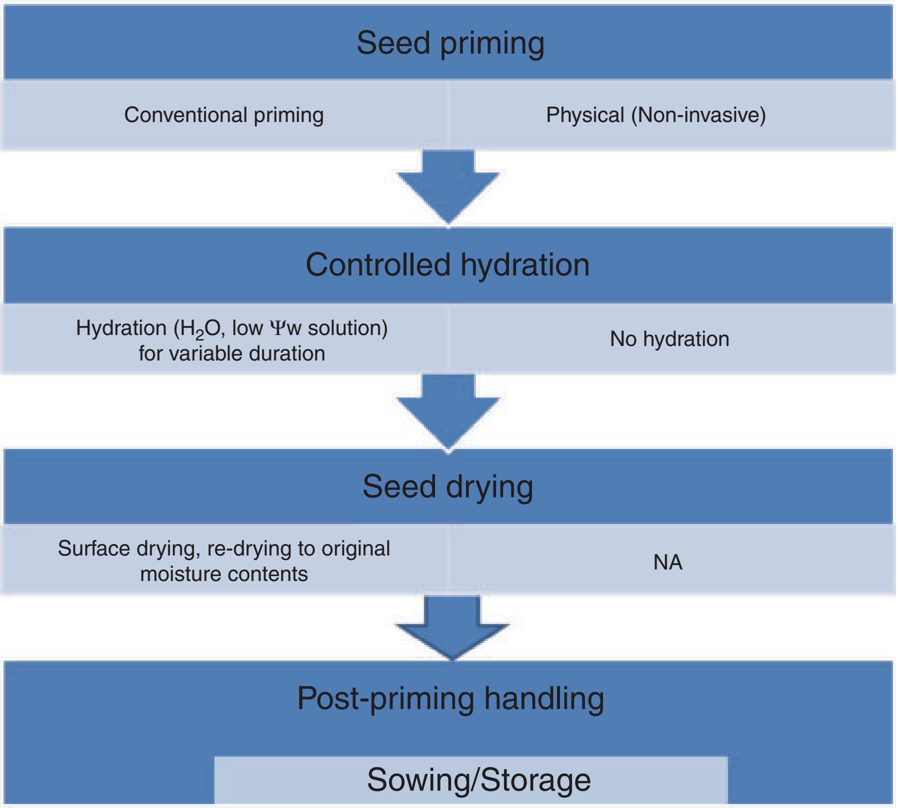

Fig. 2. Steps of seed priming from soaking to seed redrying and post-priming handling. Ψw, water potential.

priming, with some more expensive (e.g. salicylic acid (SA), proline, ascorbate, glycine betaine, plant growth hormones) than others (e.g. $CaCl_2$, NaCl, borax, crude leaf extracts); the efficacy of the former is often much better than that of the latter (Fig. 2; Basra *et al*. 2011; Jafar et al. 2012). The efficacy of chemical agents for seed priming is variable, but they can improve crop growth and yield under normal as well as stressed conditions (Basra *et al*. 2006; Naqve *et al*. 2018).

Conventional seed priming

Hydropriming

For hydropriming, seeds are soaked in tap water with or without aeration. The seeds are then dried with forced air or under shade to near their original weight (Afzal *et al*. 2002; Farooq *et al*. 2006*a*). Hydropriming is a simple, economical and environmentally friendly technique. The main disadvantage of hydropriming is that seed hydration can be irregular, resulting in non-uniform germination or crop stand (Di Girolamo and Barbanti 2012).

On-farm priming

For on-farm priming, seeds are soaked overnight in tap water without aeration and surface dried for ease of handling, followed by sowing (Rashid *et al*. 2004; Harris *et al*. 2007). On-farm priming is a low-risk, economical and simple technology that improves the processes of germination, stand establishment, succeeding growth and development and yield in a range of crops.

Seed hardening

Seed hardening involves alternating hydration and dehydration in water without aeration; this hydration–dehydration process is repeated once or twice (Lee and Kim 2000). Seed hardening is an effective treatment to improve the performance of a range of field crops under optimal and less-than-optimal conditions.

Osmopriming

Osmopriming or osmoconditioning involves soaking seeds in aerated, low-osmotic potential solutions to control water imbibition (Bray 1995; Lutts *et al*. 2016). Polyethylene glycol (PEG) is non-toxic with a large molecular size and is the most commonly used agent to lower water potential because seeds do not require piercing (Thomas *et al*. 2000). In addition, KNO_3, KH_2PO_4, $MgSO_4$, $CaCl_2$, KCl, NaCl, K_3PO_4 and mannitol can be used to achieve similar results. Osmopriming is the preferred approach for improving germination in cereals (Moradi and Younesi 2009; Farooq *et al*. 2006*a*, 2006*b*, 2006*c*, 2006*d*).

Osmohardening

Osmohardening is a relatively new technique that involves the integration of seed hardening and osmopriming (Farooq *et al*.

2006*a*). The effectiveness of seed osmohardening depends on the number and duration of cycles, as is the case for seed hardening. Osmohardening has improved the performance of direct-seeded rice (*Oryza sativa* L.; Farooq *et al*. 2006*c*, 2006*d*; Rehman *et al*. 2011*a*, 2011*b*).

Hormonal priming

Hormonal priming includes seed soaking in aerated solutions of different plant growth regulators such as ascorbate, kinetin, SA and abscisic acid. Hormonal priming has improved field crop performance on salt-affected soils (Afzal *et al*. 2006; Jafar et al. 2012; Iqbal and Ashraf 2013) and under low- and high-temperature stress (Bakhtavar *et al*. 2015).

Matripriming

In matripriming, the matric potential of water is controlled during seed hydration with solid matrix carriers that generate matrix forces to carry water and slow down its uptake by seeds upon mixing (Taylor *et al*. 1998; Paparella *et al*. 2015). The seeds are then removed from the solid carrier, cleansed and spread out to reduce the moisture content. Examples of solid matrix carriers include exfoliated vermiculite, sodium polypropionate gel, expanded calcined clay, synthetic calcium silicate, bituminous soft coal, sawdust, volcanic cinder, charcoal, sand, granulated clay particles and jute mat (Gray *et al*. 1990; Di Girolamo and Barbanti 2012; Paparella *et al*. 2015). Moreover, matrix priming uses a small amount of liquid per unit of solid particles and seed. Matripriming is more effective for seed invigoration in large-seeded crops than small-seeded crops such as rice.

Seed priming with plant leaf extracts

Commercial growth regulators can be used successfully as seed priming agents to enhance plant growth by improving germination and stand establishment. However, these are expensive and sometimes not readily available. Plant leaf extracts (e.g. moringa (*Moringa oleifera* Lam.), sorghum (*Sorghum bicolor* (L.) Moench) and sunflower (*Helianthus annuus* L.)) can be used for this purpose. Moringa leaf extract is a good source of zeatin and other plant growth promoters (Basra *et al*. 2011; Rehman *et al*. 2017). Sorghum extract contains a diverse range of soluble phenolics, such as vanillic acid, *p*-hydrobenzoic acid, *p*-hydroxybenzaldehyde, ferulic acid and *p*-coumaric acid (Einhellig and Souza 1992; Sène *et al*. 2001), that have growth-promoting potential and can be used as natural agents for seed priming (Ben-Hammouda et al. 1995; Basra *et al*. 2011). Seed priming with moringa (3%; Afzal *et al*. 2012*a*; Rehman *et al*. 2015*a*), sorghum (5%; Bajwa and Farooq 2017) or sunflower (Baldwin *et al*. 2002) leaf extracts improved the emergence rate, seedling growth and coefficient of uniformity of emergence, resulting in better plant growth in maize (*Zea mays* L.) and wheat.

Nutrient seed priming

The nutrient seed priming technique involves soaking seeds in macro- or micronutrient solutions (Farooq *et al*. 2012; Imran *et al*. 2013). Nutrient seed priming with macro- (P) and micronutrients (Zn, B, Mn) improved stand establishment, yield and grain biofortification in field crops, including wheat (Khalid and Malik 1982; Marcar and Graham 1986; Wilhelm *et al*. 1988; Nazir *et al*. 2000; Harris *et al*. 2007, 2008; Rehman *et al*. 2018*a*, 2018*b*; Nadeem and Farooq 2019; Nadeem *et al*. 2019), rice (Peeran and Natanasabapathy 1980; Slaton *et al*. 2001; Johnson *et al*. 2005; Rehman *et al*. 2013), maize (Harris *et al*. 2007, 2008; Imran *et al*. 2013; Muhammad *et al*. 2015) and chickpea (Johnson *et al*. 2005; Arif *et al*. 2007; Harris *et al*. 2008; Ullah *et al*. 2019*a*, 2019*b*). However, the concentrations of these nutrients need to be optimised to avoid nutrient toxicity and seed losses that can impair germination (Roberts 1948; Ajouri *et al*. 2004; Rehman *et al*. 2013).

Seed biopriming

Seed biopriming integrates seed hydration and a biological treatment by adding living bacterial inoculum to the medium (Moeinzadeh *et al*. 2010; Reddy 2012; Mahmood *et al*. 2016). Plant growth promoting rhizobacteria, fungicides and biocontrol agents can be added to priming media to improve seed germination and vigour, uniform crop stand, plant growth and yield attributes, including biotic and abiotic stress tolerance. Commonly used plant growth-promoting rhizobacteria include *Azotobacter*, *Pseudomonas*, *Azospirillum*, *Bacillus* and *Agrobacterium* to improve growth and yield, control seed or soil diseases and enhance abiotic stress tolerance, whereas *Trichoderma* and *Pseudomonas* improve biotic stress resistance (Reddy 2012; Mahmood *et al*. 2016).

Non-invasive priming

Physical methods for enhancing plant production offer advantages over conventional methods (Bilalis *et al*. 2012) and are based on the application of different chemical substances (Araújo *et al*. 2016). The effects of physically invigorated seed handling range from morphostructural features to changes in gene expression and metabolite accumulation. Of the available physical methods, 'magneto-priming' and ionising radiation, including gamma rays, ultraviolet (UV) rays (UVA, UVC) and X-rays, are the most promising presowing seed treatments (Araújo *et al*. 2016). The advantages of these physical methods are described below.

Magneto-priming

The effect of the magnetic field (MF), first reported in plants by Krylov and Tarakanova (1960), has received considerable attention. Magneto-primed seeds have better germination rates, root development, vigour and seedling biomass than unprimed seeds (Araújo *et al*. 2016). Plants from magneto-primed seeds also have a higher tolerance to abiotic (Anand *et al*. 2012) and biotic (De Souza *et al*. 2006) stresses due to improved α-amylase and protease activities (e.g. in maize and soybean *Glycine max* L.; Kataria *et al*. 2017). Magneto-primed soybean seeds produced fewer superoxide radicals (O_2^-; Baby *et al*. 2011). Moreover, magneto-primed seeds have the potential to minimise the adverse effects of drought and disease on crop productivity (Table 1). The MF alters the structure and ionic permeability of the cell membrane and stimulates ion transport across ion channels, which affects the metabolic pathway (Labes 1993; Khizenkov *et al*. 2001), resulting in better germination and seedling emergence.

Table 1. Effects of magnetic, gamma ray and ultraviolet irradiation priming on stand establishment and growth in different field crops
APX, ascorbate peroxidase; Chl, chlorophyll; GPX, guaiacol peroxidase; PAL, phenyl alanine lyase; ROS, reactive oxygen species; TAL, tyrosine alanine lyase

Crop	Dose (best dose)	Growing conditions and environment	Attributes	References
Magnetic priming				
Wheat (*Triticum aestivum* L.)	30 mT	Flooding	Increased activity of APX and GPX under soil flooding, lower oxidative stress	Balakhnina *et al*. (2015)
Soybean (*Glycine max* L.)	200 and 150 mT	Laboratory, field	Higher germination percentage, seedling biomass and fresh weight; improved light harvesting, Chl fluorescence, leaf photosynthetic efficiency and leaf protein content; reduced ROS production	Baby *et al*. (2011), Shine *et al*. (2011)
Sunflower (*Helianthus annuus* L.)	50 and 200 mT	Laboratory	Improved seed coat membrane activity; reduced cellular leakage; increased germination and germination rate, seedling length and biomass accumulation, root length, root surface area, enzyme activities and membrane integrity	Vashisth and Nagarajan (2010)
Mung bean (*Vigna radiata* L.)	5 mT	Laboratory	Better germination and seedling vigour; improved starch metabolism and α-amylase activity	Reddy *et al*. (2012)
Maize (*Zea mays* L.)	100 and 200 mT	Greenhouse, moisture stress	Improved seedling growth; higher leaf water status; better photosynthesis in seedlings, Chl and stomatal conductance under soil water deficit	Anand *et al*. (2012)
Faba bean (*Vicia faba* L.)	0.1 mT	–	Improved seedling growth and mitotic index	Rajendra *et al*. (2005)
Gamma ray priming				
Rice (*Oryza sativa* L.)	50–350 Gy (50 Gy)	–	Improved plant height, tiller number, panicle length and seed number per panicle at the best dose	Maity *et al*. (2005)
Maize	– (2–30 Gy)	Laboratory	Improved germination percentage, germination index and content of photosynthetic pigments at the best dose	Marcu *et al*. (2013)
Black gram (*Phaseolus mungo* L.)	50–350 Gy (200 Gy)	–	Improved plant height, pod length, seed number per pod at the best dose	Maity *et al*. (2005)
Mouse-ear cress (*Arabidopsis thaliana*)	50–100 Gy (50 Gy)	Cadmium stress	Better germination index, primary root length, seedling growth and fresh weight and antioxidant enzymes; reduced ROS and gene expression at the best dose	Qi *et al*. (2015)
UV irradiation priming	Type of UV used			
Common bean (*Phaseolus vulgaris* L.)	UVC	–	Higher germination percentage, increased accumulation of bioactive molecules (flavonoids: quercetin-3*O*-glucoside, soyasaponin)	Guajardo-Flores *et al*. (2014)
Mung bean (*Vigna radiata*)	UVA and UVC	Laboratory	Enhanced germination rate and seedling vigour; improved total Chl and carbohydrate content; seedlings less susceptible to root-infecting fungi	Hamid and Jawaid (2011), Siddiqui *et al*. (2011)
Peanut (*Arachis hypogaea* L.)	UVC	–	Enhanced germination rate and seedling vigour; improved total Chl and carbohydrate content; seedlings less susceptible to root-infecting fungi	Siddiqui *et al*. (2011)
Mash bean (*Vigna mungo* L.)	UVB	Laboratory	Reduced germination, improved activities of PAL, TAL and photosynthetic pigments	Shaukat *et al*. (2013)

Priming with gamma radiation

A powerful tool in the field of plant sciences and food technology, customarily used to tackle microbiological food safety and storability concerns, is the application of ionising radiation (Jayawardena and Peiris 1988). Gamma radiation is a high-energy class of ionising radiation, with a strong ability to interact with and penetrate living tissues. Gamma rays directly interact with several cell components at various levels and have a profound effect on nucleic acids, membranes and proteins (Kovács and Keresztes 2002; Majeed *et al*. 2018). However, reactive oxygen species (ROS) are produced indirectly from the radiolysis of water (Esnault *et al*. 2010) and can adversely affect various cellular organelles and macromolecules. At low doses, gamma rays can act as a 'priming agent' by improving germination percentage and seedling establishment under optimal and suboptimal conditions.

Gamma rays as ionising radiation affect plant growth and development by inducing cytological, biochemical, physiological and morphological changes in cells and tissues by producing free radicals in cells (Kim *et al*. 2004; Wi *et al*. 2005). Higher doses of gamma radiation can be inhibitory for seed germination and plant growth (Kumari and Singh 1996), whereas lower doses can be stimulatory. Low doses of gamma rays have been reported to increase cell proliferation, germination, cell growth, enzyme activity, stress resistance and crop yields (Baek *et al*. 2005; Kim *et al*. 2005; Calabrese and Blain 2009; Jan *et al*. 2012). The effect of exposure to gamma radiation was studied in seeds of the maize hybrid Turda Star (Marcu *et al*. 2013), with beneficial stimulatory effects recorded at low doses ranging from 2 to 30 Gy, whereas higher doses (≥70 Gy) had a negative effect on plant performance. Melki and Sallami (2008) showed that seed treatment with low doses of gamma rays significantly elongated the root system in chickpea plants. Geras'kin *et al*. (2017) exposed barley seeds to gamma radiation (2–50 Gy); maximum growth stimulation occurred at 2–16 Gy due to the higher enzyme activation at these levels.

The biological, molecular and subcellular mechanisms underlying the beneficial effects of radiation are debatable. Several researchers have reported that seed exposure to gamma rays increases ROS production, which act as signalling molecules to trigger and magnify stress and antioxidant responses in seeds. As a result, irradiated plants can overcome daily stress factors, such as fluctuations in temperature, light intensity and water loss during growth (Gicquel *et al*. 2012; Qi *et al*. 2015; Table 1).

UV irradiation priming

The portion of solar UV radiation touching the Earth's surface is expanding as a consequence of the depletion of the ozone layer in the stratosphere. UV radiation is divided into three categories according to wavelength: UVA (320–400 nm), UVB (280–320 nm) and UVC (200–280 nm). Researchers have addressed the global effect of UV exposure on plant species at various levels, from single plants to an entire ecosystem (Kovács and Keresztes 2002). However, few studies have been devoted to investigating the effects of UV exposure on seed biology.

UVC radiation is non-ionising radiation that superficially penetrates plant tissues and can act as a germicidal agent, but is extremely harmful to living organisms. Seed priming with low doses of UVC (3.6 kJ m^{-2}) induced various morphological and physiological changes in wheat, rice, maize and cowpea (*Vigna unguiculata* L. Walp), including increased germination rate, biomass and photosynthesis (Thomas and Puthur 2017). The same authors showed that UVB radiation priming (6 kJ m^{-2}) improved photosystem I and photosystem II activity, chlorophyll-*a* fluorescence, metabolite accumulation (proline, total sugars) and enzymatic and non-enzymatic antioxidants in rice seedlings compared with unprimed seeds (Thomas and Puthur 2017). UVA radiation, the least hazardous category of UV radiation, represents only 6.3% of incoming solar radiation (Hollósy 2002). Information on the application of UVA radiation as a seed invigoration tool is rare. Treating wheat seeds with UVC radiation can stimulate germination (Rupiasih and Vidyasagar 2016), and UV radiation has been reported to induce rapid germination in different wheat cultivars (Sakha-94, Gemmiza-9, Giza-168) due to an increase in seed germination percentage and germination rate (Abu-Elsaoud and Hassan 2016).

X-Ray priming

In the electromagnetic spectrum, the wavelength of X-rays ranges from 0.01 to 10 nm (Kotwaliwale *et al*. 2014), and their effects on living organisms are not fully recognised. Soft X-rays, with energies of approximately 0.12–12 keV, are the most beneficial for agricultural studies due to their low penetration potential (Kotwaliwale *et al*. 2014). Moreover, food treatment with X-rays can improve microbiological food safety and storability (Farkas and Mohácsi-Farkas 2011). Few studies have focused on the effects of X-ray irradiation on seed performance (De Micco *et al*. 2014). The physiological and molecular mechanisms underlying the resistance of plant tissues to X-rays could be revealed by manipulating global profiling techniques (e.g. omics; Araújo *et al*. 2016).

Smoke priming

Priming with a smoke solution is considered a cheap and cost-effective way to enhance plant growth and germination in the ecosystem (Brown and Botha 2004). Smoke priming not only improves germination, but also has a beneficial effect on flowering and somatic embryogenesis (Keeley 1993; Senaratna *et al*. 1999). Plant-derived smoke is a composite chemical mixture containing the active plant compound 3-methyl-2*H*-furo[2,3-*c*]pyran-2-one (butenolide; van Staden *et al*. 2006) that stimulates seed germination (Dixon *et al*. 2009), seedling growth and vigour (Sparg *et al*. 2006; Kulkarni *et al*. 2011; Iqbal *et al*. 2016). Moreover, plant-derived smoke solutions induce tolerance to abiotic stresses (van Staden *et al*. 2006) such as salinity (Malook *et al*. 2017). Priming with smoke-derived compounds, such as karrkinolide, has the potential to enhance seed germination, seedling emergence and catalase activity, but may reduce superoxide dismutase (SOD) and ascorbate peroxidase activity (Demir *et al*. 2018). Smoke priming alleviates the harmful effects of salt stress on rice by protecting the plant against ion toxicity, reducing sodium ion uptake and increasing potassium ions in roots and shoots (Malook *et al*. 2017). Soaking rice seeds for 24 h in smoke derived from *Cymbopogon jwarancusa* and *Bauhinia variegata* induced salinity tolerance (Jamil *et al*. 2013).

Benefits of seed priming

Stand establishment and growth

Seed priming improves stand establishment, crop growth and yield under optimal conditions (Farooq *et al*. 2006*a*, 2006*b*, 2006*c*, 2006*d*, 2008*a*, 2008*b*), as well as under suboptimal conditions, such as salinity (Jafar et al. 2012), drought and temperature extremes (Farooq *et al*. 2008*b*, 2008*c*; Bakhtavar *et al*. 2015). Osmopriming and osmohardening (with $CaCl_2$ and KCl), seed hardening and hydropriming improve seedling emergence and stand establishment in various field crops, including maize, rice, wheat, linola and chickpea (Table 2; Farooq *et al*. 2006*a*, 2006*b*, 2006*c*, 2007*a*, 2008*a*; Rehman *et al*. 2011*a*, 2011*b*, 2014*a*, 2015*a*, 2015*b*). Each of these priming techniques has been optimised with regard to the concentration of different plant growth regulators, micronutrients, osmotica and plant-based leaf extracts, including water and soaking or hydration duration (Table 2). After sowing, primed seeds emerge quickly due to moisture availability and explore more soil nutrient resources to produce vigorous seedlings with uniform crop stands (Table 2). Vigorous crop stands are due to the efficient remobilisation of nutrients to the growing embryonic axis (Kathiresan *et al*. 1984). In addition, primed field-sown crops usually complete other phenological events, such as flowering, earlier than non-primed crops (Farooq *et al*. 2006*c*, 2006*d*, 2012; Rehman *et al*. 2013, 2017). Such plasticity in phenology can be helpful when integrated with other crop husbandry practices, particularly in water, temperature and nutrient management stress to avoid their detrimental effects during early and later reproductive stages without yield penalty. Early and vigorous crop stands usually capture more water and nutrient resources due to a better root system and have larger leaf areas and duration with enhanced photo-assimilation to improve yields (Farooq *et al*. 2012; Fig. 1).

Rice seeds hydroprimed for 12, 24, 36 and 48 h had enhanced vigour, improved germination-related attributes and increased seedling root and shoot lengths and fresh and dry weights (Farooq *et al*. 2006*a*). Matripriming improved crop performance, including stand establishment and seedling growth of maize exposed to salt stress (Zhang *et al*. 2007). Priming of direct-seeded rice with selenium and SA improved chilling stress tolerance by enhancing α-amylase activity and soluble sugar content (Wang *et al*. 2016). Matripriming with sand reduced mean emergence time, improved seedling fresh and dry weights and enhanced plant height in maize compared with unprimed seeds (Zhang *et al*. 2007). Priming is a convenient alternative technique for improving stand establishment and growth in various crops (Tables 2, 3). In maize, halopriming with KCl induced chilling tolerance and increased final germination, the germination index and early seedling growth (Farooq *et al*. 2008*c*). Priming with KCl is the most effective technique for improving stand establishment in coarse rice (Farooq *et al*. 2006*a*, 2006*b*, 2006*c*), growth in nursery rice seedlings (Farooq *et al*. 2007*a*) and performance of transplanted rice (Farooq *et al*. 2007*a*, 2007*b*).

The effects of irradiation, such as gamma rays, UVA and UVB, are dose dependent, with lower doses (<100 Gy) having beneficial effects on germination-related attributes and seedling establishment under various conditions (Maity *et al*. 2005; Hamid and Jawaid 2011; Emrani *et al*. 2013; Shaukat *et al*. 2013; Qi *et al*. 2015). Such beneficial effects of radiation were associated with higher germination rates and better seedling performance in *Arabidopsis thaliana*, rice, mung bean (*Phaseolus mungo* L.) and mash bean (*Vigna mungo* L. Hepper) due to improved root and shoot lengths, specific leaf areas and dry weights.

Yield benefits

Seed priming that induces earlier emergence and uniform crop stands is usually associated with higher growth rates, dry matter, yield and quality under biotic and abiotic stresses (Fig. 1; Table 2). In most studies investigating seed priming under conditions of saline or low temperature stress, seed priming increased yield by a similar percentage under stressed and non-stressed conditions.

The benefits of seed priming may be greater under suboptimal than optimal conditions. Nonetheless, higher yields with priming techniques in different crop types, particularly cereals under normal and abiotic stress, may be associated with higher field emergence, fertile tillers and growth traits (leaf area, crop growth rate and leaf area duration) during later stages, including the maintenance of photosynthetic activity associated with high chlorophyll contents during the reproductive period (Tables 2 and 3).

Further increases in yield have been associated with high competitive advantage over weeds, increased leaf area and more panicles per unit area in direct-seeded rice under aerobic and submerged conditions (Mahajan *et al*. 2011; Anwar *et al*. 2012; Sarkar 2012), improved nutritional status in maize plants under chilling stress (Imran *et al*. 2013), increased dry matter and tissue Zn concentrations in Zn-primed rice (Slaton *et al*. 2001), more fertile tillers associated with reduced spikelet sterility and higher growth rates and tillering in direct-seeded rice irrigated with alternate wetting and drying (AWD) and system of rice intensification (Khalid *et al*. 2015; Rehman *et al*. 2015*b*). It is likely that a higher leaf area index and maintenance of green area duration at maturity in no-tilled wheat was due to the induction of early seedling vigour by seed priming (Rehman *et al*. 2015*a*), synchronised and uniform stand establishment (Nawaz *et al*. 2016; Nadeem *et al*. 2019) and improved tiller emergence and panicle fertility with boron nutrition under aerobic or AWD conditions (Rehman *et al*. 2016). It is likely that gibberellic acid (GA_3) modulated Na^+ and K^+ uptake and hormone homeostasis in salt-stressed wheat (Iqbal and Ashraf 2010), the combined effect of gypsum and farmyard manure ameliorated salinity effects on plant growth (Shah *et al*. 2013) and improved performance of low vigour wheat and barley seeds under drought stress (Hussain *et al*. 2013; Tabassum *et al*. 2018*a*). Nonetheless, a few studies have reported no yield improvement after seed priming (Johnson *et al*. 2005; Subedi and Ma 2005). Many researchers have reported higher grain yields due to seed priming-induced improvements in stand establishment, growth and development in agronomic and horticultural crops (Tables 2 and 3).

Thus, seed priming offers a promising and economical solution for improving crop resistance to low and high temperature, flooding, drought, salinity and nutrient stress.

Table 2. Effects of seed priming treatments on stand establishment, growth and grain yield in different field crops

[Zn(Gln)$_2$], zinc glutamine; [Zn(His)$_2$], zinc histidine; As, arsenic; ASA, ascorbic acid; AWD, alternate wetting and drying; B, boron; Chl, chlorophyll; DM, dry matter; DSR, direct-seeded rice; EC, electrical conductivity; IAA, indole acetic acid; MLE, moringa water extract; PEG, polyethylene glycol; PSB, phosphate-solubilising bacteria; PTR, puddled transplanted rice; SA, salicylic acid; SNP, sodium nitroprusside; SRI, system of rice intensification; SWE, sorghum water extract; TSPhe, total soluble phenolics; TSPr, total soluble protein; WUE, water use efficiency

Crop	Seed treatment	Growing conditions and environment	% Decrease in mean emergence time over control	% Increase in emergence over control	% Increase in yield over control	Plant traits measured and mechanism studied	References
Wheat	Hydropriming	Field, zero tillage	1.86–9.31	–	3.8–5.3	Improved stand establishment, grain yield, profitability	Mustafa *et al*. (2018)
	Osmopriming	Field, conventional tillage	2.35–10	–	7.08–8.3	Improved stand establishment, grain yield, profitability	Mustafa *et al*. (2018)
	Seed priming with Zn (0.5 M, 12 h)	Field	–	–	178–22	Improved yield, grain biofortification (Zn concentration in embryo, aleurone, endosperm); decreased phytate contents	Rehman *et al*. (2018*b*)
	Seed priming with *Pseudomonas* sp. (Mn 12 M + Zn 0.5 M, 12 h)	Field	–	–	198–27	Improved yield, grain biofortification (Zn concentration in embryo, aleurone, endosperm); decreased phytate contents	Rehman *et al*. (2018*b*)
	Seed priming with *Pseudomonas* sp. (Mn 12 M + Zn 0.5 M, 12 h)	Field	–	–	–	Improved photosynthetic assessment; enhanced grain Zn concentration and grain yield	Rehman *et al*. (2018*a*, 2018*b*)
	Nutripriming (Se)	As stress, greenhouse	–	–	4.78–19.7	Promoted growth and yield, improved Chl, reduced As translocation	Moulick *et al*. (2018)
	Osmopriming (SNP)	Salinity stress, greenhouse	–	–	22.5	Improved grain yield; reduced oxidative stress; increased activity of antioxidant enzymes	Ali *et al*. (2017)
	Osmopriming (SNP)	Salinity stress, greenhouse	–	–	21.8	Improved grain yield, reduced oxidative stress, increased activity of antioxidant enzymes	Ali *et al*. (2017)
	Osmopriming (SNP)	Salinity stress, greenhouse	–	–	9.5	Improved grain yield; reduced oxidative stress; increased activity of antioxidant enzymes	Ali *et al*. (2017)
	Osmopriming (SNP)	Salinity stress, greenhouse	–	–	10.0	Improved grain yield; reduced oxidative stress; increased activity of antioxidant enzymes	Ali *et al*. (2017)
	Seed priming (SWE)	Greenhouse	18.51	–	–	Improved germination, Chl content, accumulation of TSPr, TSPhe, α-amylase activity	Bajwa and Farooq (2017)
	Seed priming (benzyl aminopurine)	Greenhouse	20.37	–	–	Improved germination, Chl content, accumulation of TSPr, TSPhe, α-amylase activity	Bajwa and Farooq (2017)
	Osmopriming ($CaCl_2$)	Vegetative drought, sown in different-spaced rows	–	–	14.5	Increased grain yield, WUE, profitability	Hussain *et al*. (2016*c*)
	Osmopriming ($CaCl_2$)	Vegetative drought, sown in different-spaced row	–	–	11.1	Increased grain yield, WUE, profitability	Hussain *et al*. (2016*c*)
	Osmopriming ($CaCl_2$)	Vegetative drought, sown in different-spaced row	–	–	7.1	Increased grain yield, WUE, profitability	Hussain *et al*. (2016*c*)

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Osmopriming ($CaCl_2$)	Field, irrigated	–	–	8.58–9.6	Increased grain yield and economic benefit; improved allometric traits and WUE	Farooq *et al.* (2017*b*)
Osmopriming ($CaCl_2$)	Field, vegetative drought stress	–	–	6.88–18.2	Increased grain yield and economic benefit; improved allometric traits and WUE	Farooq *et al.* (2017*b*)
Osmopriming ($CaCl_2$)	Field, terminal drought stress	–	–	19.68–37.2	Increased grain yield and economic benefit; improved allometric traits and WUE	Farooq *et al.* (2017*b*)
Nutripriming (Mn)	Field, nutrient stress[A]	–	–	10	Improved productivity, Mn grain biofortification and economic benefit	Ullah *et al.* (2018*a*)
Osmopriming (KCl)	Field, broadcast, row plantation	–	2.67	11	Improved crop emergence, reduced weed density, increased grain yield	Ullah *et al.* (2018*b*)
Hydropriming	Field, plough till wheat after DSR	10.978–20.77	–	3.18–5.9	Improved stand establishment, grain yield, water productivity	Nawaz *et al.* (2016)
Hydropriming	Field, no-till wheat after DSR	10.128–23.94	–	2.08–8.6	Improved stand establishment, grain yield, water productivity	Nawaz *et al.* (2016)
Hydropriming	Field, plough till wheat after PTR	5.48–15.01	–	5.58–7.2	Improved stand establishment, grain yield, water productivity	Nawaz *et al.* (2016)
Hydropriming	Field, no-till wheat after PTR	9.628–20.85	–	0.38–13.5	Improved stand establishment, grain yield, water productivity	Nawaz *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, plough till wheat after DSR	6.38–11.91	–	13.58–17.6	Improved stand establishment, grain yield, water productivity and economic profitability	Nawaz *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, no-till wheat after DSR	5.328–19.37	–	11.68–22.5	Improved the stand establishment, grain yield, water productivity and economic profitability	Nawaz *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, plough till wheat after flooded rice	7.298–13.2	–	8.98–18.2	Improved stand establishment, grain yield, water productivity and economic profitability	Nawaz *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, no-till wheat after flooded rice	9.68–23.28	–	13.78–25.2	Improved stand establishment, grain yield, water productivity and economic profitability	Nawaz *et al.* (2016)
Nutripriming ([$Zn(Gln)_2$], 40 mg L^{-1})	Nutrient stress[A]	–	–	46	Improved grain protein content, grain yield	Seddigh *et al.* (2016)
Nutripriming ([$Zn(His)_2$], 40 mg L^{-1})	Nutrient stress[A]	–	–	14	Increased Fe and Zn accumulation in grain	Seddigh *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, zero tillage	2.5	–	5.8	Improved growth, leaf area index, net assimilation rate and grain yield	Haider *et al.* (2016)
Osmopriming ($CaCl_2$)	Field, conventional tillage	6.5	–	4.2	Improved growth, leaf area index, net assimilation rate and grain yield	Haider *et al.* (2016)
Hydropriming	Lysimeter, drought stress	–	–	3.7	Improved yield and quality, osmoprotectants and antioxidant activities	Nawaz *et al.* (2015)
Nutripriming (Se)	Lysimeter, drought stress	–	–	18.2	Improved yield and quality, osmoprotectants and antioxidant activities	Nawaz *et al.* (2015)

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Osmopriming ($CaCl_2$)	Field, late-sown wheat	24.4	–	19.2	Enhanced stand establishment and grain yield; improved allometric traits	Hussain *et al.* (2013)
Hydropriming	Farmer's field, salinity stress	3.4–8.8	–	21.6	Improved stand establishment and grain yield	Jafar *et al.* (2012)
Hormonal priming (ascorbate)	Farmer's field, salinity stress	10–17.6	–	38.4	Improved stand establishment and grain yield; increased economic benefit; improved leaf K^+ content, TSPhe, TSPr and α-amylase activity	Jafar *et al.* (2012)
Osmopriming ($CaCl_2$)	Farmer's field, salinity stress	10–20.56	–	53.6	Improved stand establishment and grain yield; increased economic benefit; improved leaf K^+ content, TSPhe, TSPr and α-amylase activity	Jafar *et al.* (2012)
Hormonal priming (SA)	Farmers field, salinity stress	3.41–14.65	–	24.6	Improved stand establishment and grain yield; increased economic benefit; improved leaf K^+ content, TSPhe, TSPr and α-amylase activity	Jafar *et al.* (2012)
Hormonal priming (kinetin)	Farmer's field, salinity stress	7.18–17.65	–	8.8	Improved stand establishment and grain yield; increased economic benefit; improved leaf K^+ content, TSPhe, TSPr and α-amylase activity	Jafar *et al.* (2012)
Nutripriming (B)	–	20	–	–	Improved root and shoot length, seedling dry weight	Iqbal *et al.* (2012)
Osmopriming (spermidine)	Controlled environment	31.0	–	–	Improved germination; reduced EC of seed leachates; improved starch metabolism	Farooq *et al.* (2011*b*)
Osmopriming (spermine)	Controlled environment	22.0	–	–	Improved germination, lower EC of seed leachates, improved starch metabolism	Farooq *et al.* (2011*b*)
Osmopriming (putrescine)	Controlled environment	18.9	–	–	Improved germination; reduced EC of seed leachates; improved starch metabolism	Farooq *et al.* (2011*b*)
Hydropriming	Farmer's field, chilling stress	26.6	–	11.2	Improved emergence, stand establishment, allometry and grain yield	Farooq *et al.* (2008*a*)
Osmopriming (KCl)	Farmer's field, chilling stress	33.3	–	24.1	Improved emergence, stand establishment, allometry and grain yield	Farooq *et al.* (2008*a*)
Osmopriming ($CaCl_2$)	Farmer's field, chilling stress	33.3	–	33.7	Improved emergence, stand establishment, allometry and grain yield	Farooq *et al.* (2008*a*)
Hydropriming	Field, late-sown wheat	–	–	12.6–16.0	Enhanced plant DM; increased grain yield	Kant *et al.* (2004)
Hormonal priming (IAA)	Field, late winter sown	–	–	10.4–13.1	Enhanced plant DM; increased grain yield	Kant *et al.* (2004)

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	Osmopriming (KCl)	Field, late winter sown	–	–	8.4–8.5	Enhanced plant DM; increased grain yield	Kant *et al*. (2004)
	Nutripriming ($ZnSO_4$)	Field, late winter sown	–	–	6.8–7.0	Enhanced plant DM; increased grain yield	Kant *et al*. (2004)
	Osmopriming (Na_2SO_4)	Field, late winter sown	–	–	12.6–16.0	Enhanced plant DM; increased grain yield	Kant *et al*. (2004)
	Osmopriming (Gypsum)	Field, salinity stress	–	–	5–3	Early emergence; vigorous growth; higher grain yield	Harris *et al*. (2001)
	Osmopriming ($NaHCO_3$)	Field	–	–	10	–	Singh and Gill 1988)
Rice	Nutripriming (Zn)	Field, DSR and PTR	–	–	2.4–3.4	Improved yield, grain Zn concentration	Farooq *et al*. (2018)
	Nutripriming (Zn)	Field, DSR	–	–	34.6	Improved yield, grain Zn concentration	Farooq *et al*. (2018)
	Nutripriming (Zn)	Field, PTR	–	–	41.1	Improved yield, grain Zn concentration	Farooq *et al*. (2018)
	Hydropriming	Field, DSR	–	–	5.8	Improved growth, morphological yield-related traits, grain yield	Rehman *et al*. (2016)
	Nutripriming (B)	Field, DSR	–	–	10.5–24.6	Improved growth, water relationships, morphological yield-related traits, grain yield, economic benefits	Rehman *et al*. (2016)
	Hydropriming	Field, AWD	–	–	–3.2 to –1.5	Improved growth, morphological yield-related traits, grain yield	Rehman *et al*. (2016)
	Nutripriming (B)	Field, AWD	–	–	15.6–27.0	Improved growth, water relationships, morphological yield-related traits, grain yield, economic benefits	Rehman *et al*. (2016)
	Hydropriming	Field, flooded rice	–	–	7.4–7.9	Improved growth, morphological yield-related traits, grain yield	Rehman *et al*. (2016)
	Nutripriming (B)	Field, flooded rice	–	–	27.0	Improved growth, water relationships, morphological yield-related traits, grain yield, economic benefits	Rehman *et al*. (2016)
	Osmopriming (KCl)	Field, DSR-AWD	–	5.78	1.4–17.7	Improved emergence and grain yield	Rehman *et al*. (2015*b*)
	Osmopriming ($CaCl_2$)	Field, DSR-AWD	–	11.21	7.6–20.6	Improved emergence and grain yield	Rehman *et al*. (2015*b*)
	Hormonal priming (MLE)	Field, DSR-AWD	13.09	53.17	18.7–21.4	Improved emergence, grain yield, grain quality	Rehman *et al*. (2015*b*)
	Hydropriming	Field, DSR	–	–	4.4–14.9	Improved water relationships, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Nutripriming (B)	Field, DSR	–	–	9.7–25.9	Improved water relationships, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Nutripriming (B)	Field, AWD	–	–	21.0–25.5	Improved water relationships, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Hydropriming	Field, AWD	–	–	10.5–11.2	Improved water relationships, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Hydropriming	Field, flooded rice	–	–	–1.4 to –2.5	Improved water relationship, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Nutripriming (B)	Field, flooded rice	–	–	12.5–20.3	Improved water relationships, Chl content, kernel yield, grain quality	Rehman *et al*. (2014*b*)
	Osmopriming ($CaCl_2$)	Field, DSR-SRI	15.2	–	31.5	Enhanced stand establishment; increased grain yield and net benefit	Ahmad *et al*. (2013)

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Hydropriming	Field, DSR-SRI	14.5	–	36	Enhanced stand establishment; increased grain yield and net benefit	Ahmad *et al*. (2013)
On-farm priming	Field, DSR-SRI	14.5	–	34.7	Enhanced stand establishment; increased grain yield and net benefit	Ahmad *et al*. (2013)
Hydropriming	Greenhouse-DSR	3.45–5.3	–	–	Increased emergence, seedling growth, yield-related traits, grain yield	Rehman *et al*. (2012)
Nutripriming (B)	Greenhouse-DSR	3.3–6.2	–	–	Increased emergence, seedling growth, grain yield, Chl content, grain B content	Rehman *et al*. (2012)
Nutripriming (B)	Greenhouse-DSR	–7.1	–	–	Increased emergence, seedling growth, grain yield, Chl content, grain B content	Rehman *et al*. (2012)
Nutripriming (B)	Laboratory	–	–	–	Improved emergence, germination energy, germination index	Farooq *et al*. (2011*c*)
Hydropriming	Field, DSR	0.9	–2.8	–18.3	Improved stand establishment, allometric response, grain yield, grain quality	Rehman *et al*. (2011*b*)
Osmopriming ($CaCl_2$)	Field, DSR	3.7	23.2	27.0	Higher crop growth rate; improved yield-related attributes and grain yield	Rehman *et al*. (2011*b*)
Osmopriming (KCl)	Field, DSR	2.8	10.1	0	Improved P, Ca and K contents in kernel	Rehman *et al*. (2011*b*)
Osmopriming (KH_2PO_4 0.5%, 1%; $CaCl_2$ 0.5%, 1%; PEG 10%, 20%; KCl 0.5%, 1%, 1.5%; distilled water and a control) for 12, 34 and 36 h	Laboratory	–	–	–	Higher vigour index, stem and radicle lengths, germination percentage, germination index	Yari and Sheidaie 2011)
Hydropriming for 48 h, osmohardening with KCl and $CaCl_2$, ascorbate priming, hardening and pregermination	Controlled environment	–	–	–	Lower emergence time; higher emergence index; increased seedling length, root numbers, fresh and dry mass, α-amylase activity and reducing sugars	Farooq *et al*. (2010)
Hydropriming	Field, flooded rice	13.1	–	26.7	Increased germination rate, root growth, grain yield	Farooq *et al*. (2007*b*)
Osmopriming (KCl)	Field, flooded rice	27.1	–	33.3	Improved germination rate, seedling vigour, starch metabolism; increased Ca and K content, grain yield	Farooq *et al*. (2007*b*)
Osmopriming ($CaCl_2$)	Field, flooded rice	34.0		42.8	Improved germination rate, seedling vigour, starch metabolism; increased Ca and K content, grain yield	Farooq *et al*. (2007*b*)
Hormonal priming (ascorbate)	Field, flooded rice	27.1	–	23.8	Improved germination rate, seedling vigour, starch metabolism; increased Ca and K content, grain yield	Farooq *et al*. (2007*b*)
Hydropriming	Farmer's field, DSR	9.9	6.25	3.7	Uniformity in stand establishment; higher grain yield	Farooq *et al*. (2006*d*)

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	Osmopriming (KCl)	Farmer's field, DSR	28.7	10	18.5	Synchronised germination; increased α-amylase activity, total sugars, grain yield	Farooq *et al*. (2006*d*)
	Osmopriming ($CaCl_2$)	Farmer's field, DSR	21.2	10	14.8	Synchronised germination; increased α-amylase activity, total sugars, grain yield	Farooq *et al*. (2006*d*)
	Hormonal priming (ascorbate)	Farmer's field, DSR	10.6	2.5	11.1	Synchronised germination; increased α-amylase activity, total sugars, grain yield	Farooq *et al*. (2006*d*)
	Osmopriming (KCl)	Farmer's field, DSR	–	–	3–18	Faster germination; improved α-amylase activity, grain yield and quality	Farooq *et al*. (2006*c*)
	Hormonal priming (ascorbate)	Growth chamber	–	–	–	Higher germination; better seedling growth	Basra *et al*. (2006)
	Hardening for 24 and 48 h, osmoconditioning (–1.1 MPa KNO_3)	Growth chamber	–	–	–	Higher germination percentage, germination index and energy of germination; lower mean emergence time; higher reducing and total sugars and α-amylase activity	Basra *et al*. (2005)
Maize	Nutripriming (B + Zn)	Field, semi-arid conditions	16.8	–	17.7	Early emergence; higher grain yield and protein content	Rasool *et al*. (2019)
	Nutripriming (B + Mn)	Field, semi-arid conditions	19.4	–	13.9	Early emergence; higher grain yield and protein content	Rasool *et al*. (2019)
	Nutripriming (B + Zn + Mn)	Field, semi-arid conditions	21.6	–	23.3	Early emergence; higher grain yield and protein content	Rasool *et al*. (2019)
	Hydropriming	Field, low temperature	4.0	28.8	29.1	Higher germination, crop growth rate, Chl content, relative water content, photosynthetic activity; improved grain-filling period	Bakhtavar *et al*. (2015)
	Hydropriming	Field, optimal temperature	3.6	5.8	34.1	Higher germination, crop growth rate, Chl content, relative water content, photosynthetic activity; improved grain-filling period	Bakhtavar *et al*. (2015)
	Hormonal priming (MLE)	Field, low temperature	2.4	27.7	37.7	Higher germination, crop growth rate, Chl content, relative water content, photosynthetic activity; improved grain-filling period	Bakhtavar *et al*. (2015)
	Hormonal priming (MLE)	Field, optimal temperature	3.1	5.8	28.8	Higher germination, crop growth rate, Chl content, relative water content, photosynthetic activity; improved grain filling period	Bakhtavar *et al*. (2015)
	Hydropriming	Growth chamber, nutrient stress[A]	–	–	2.1	Improved grain yield	Imran *et al*. (2015)
	Nutripriming (Zn + Mn)	Growth chamber, nutrient stress[A]	–	–	15.1	Higher grain yield and nutrient translocation to grain	Imran *et al*. (2015)
	Nutripriming (B)	Growth chamber, nutrient stress[A]	–	–	6.3	Better translocation of seed reserves to shoots; higher grain yield	Imran *et al*. (2015)

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	Nutripriming (P)	Growth chamber, nutrient stress[A]	–	–	5.4	Better translocation of seed reserves to shoots; higher grain yield	Imran *et al*. (2015)
	Hydropriming	Field, late sown maize	0.66	–	5.1	Better germination and grain yield	Mahboob *et al*. (2015)
	Osmopriming ($CaCl_2$)	Field, late sown maize	10.5	–	4.9	Uniform crop stand; more grains per cob; increased grain yield and grain protein content	Mahboob *et al*. (2015)
	Hormonal priming (MLE)	Field, late-sown maize	1.3	–	13.2	Improved Chl-*a* and -*b* content; increased grain yield	Mahboob *et al*. (2015)
	Hydropriming	Field, early planted spring maize	5	–	4.7	Improved crop growth and leaf water contents; higher grain yield	Rehman *et al*. (2015*a*)
	Osmopriming ($CaCl_2$)	Field, early planted spring maize	28.75	–	17.9	Reduced EC; increased relative leaf water content, Chl content, net assimilation rate; higher grain yield	Rehman *et al*. (2015*a*)
	Hormonal priming (MLE)	Field, early planted spring maize	0	–	38.7	Reduced EC; increased relative leaf water content, Chl content, net assimilation rate; higher grain yield	Rehman *et al*. (2015*a*)
	Hormonal priming (SA)	Field, early planted spring maize	26.6	–	34.9	Reduced EC; increased relative leaf water content, Chl content, net assimilation rate; higher grain yield	Rehman *et al*. (2015*a*)
	Hormonal priming (ascorbate)	Field, greenhouse, Al stress	–	–	62.5	Reduced oxidative stress enzymes; increased productivity	Alcântara *et al*. (2015)
	Priming (SA + H_2O_2, ASA + H_2O_2 + SA, MLE + SWE + H_2O_2)	Growth chamber, low temperature	–	–	–	Higher final germination percentage and germination index	Imran *et al*. (2013)
	Priming with MLE (1:30 dilution in water)	Laboratory	–	–	–	Improved germination	Basra *et al*. (2011)
	Osmopriming (KNO_3)	Field	–	–	25	Increased grain yield	Bakht *et al*. (2010)
	Hormonal priming (MLE)	Field	–	–	20–35	Increased grain yield	Foidle *et al*. (2001)
Cowpea (*Vigna unguiculata* L.)	Osmopriming (NaCl, KNO_3) and hydropriming	Laboratory, field, rain-fed environment	–	–	–	Higher seedling emergence and establishment	Eskandari and Kazemi (2011)
Chickpea (*Cicer arietinum* L.)	Hydropriming and osmopriming with mannitol 4%	Field	–	–	–	More seeds and higher yield per plant; increased activity of invertase and sucrose synthase at grain filling	Kaur *et al*. (2005)
	Nutripriming (Zn 0, 25, 50 and 75 µM)	Laboratory	–	–	–	Increased grain Zn concentration; higher peroxidase activity to compensate for higher level of H_2O_2	Tajlil *et al*. (2014)
Sorghum (*Sorghum bicolor*)	Osmopriming with PEG (6000) and hydropriming (12, 24 and 36 h)	Laboratory, suboptimal temperature (15°C)	–	–	–	Higher emergence percentage and emergence rate at 12 and 24 h	Moradi and Younesi (2009)
Mung bean	On-farm priming	Field	–	–	–	Increased pod yield (by 264%), grain yield (by 425%); reduced symptoms of mungbean yellow mosaic virus	Rashid *et al*. (2004)

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Kidney bean (*Phaseolus vulgaris* L.)	Hydropriming for 12, 24 h	Laboratory	–	–	–	Higher germination (96%), seedling dry weight and vigour	Maroufi *et al.* (2011)
Sunflower	Biopriming with *Pseudomonas fluorescens* (UTPf76 and UTPf86)	Laboratory, greenhouse				Higher germination (index, percentage and rate), vigour index and seedling growth indices (shoot height, root length, fresh and dry weight of seedlings and lateral root numbers)	Moeinzadeh *et al.* (2010)
Linola (*Linum*	*usitatissimum* L.)	Seed inoculation with PSB, *Bacillus* sp.	Field	10.9	–	2.7	Improved seedling vigour; increased total Chl content and seed yield; reduced P application
Irshad *et al.* (2016)							
	Hydropriming	Field	15.7	–	2.7	Higher germination rate, Chl content	Irshad *et al.* (2016)
	Nutripriming (P)	Field	7.1	–	–20	Higher grain yield, oil percentage and economic benefits	Irshad *et al.* (2016)
	Hydropriming	Field	1.1	16.3	10.1	Increased emergence, seedling dry weight, grain yield	Rehman *et al.* (2014*a*)
	Osmopriming ($CaCl_2$)	Field	1.6	13.2	39.5	Increased emergence, seedling dry weight and Chl content; improved yield-related traits and grain yield	Rehman *et al.* (2014*a*)
	Hormonal priming (MLE)	Field	1.3	15.8	24.3	Higher emergence, seedling dry weight and Chl content; improved yield-related traits and grain yield	Rehman *et al.* (2014*a*)

[A]The crop was sown on a soil deficient in the particular nutrient.

Table 3. Effects of seed priming treatments on growth, phenology and grain yield in different field crops
B, boron; CGR, crop growth rate; IAA, indoleacetic acid; LAD, leaf area duration; LAI, leaf area index; MLE, moringa water extract; SA, salicylic acid

Crop	Seed priming type	Growing conditions	% Increase or decrease in tillering	Crop growth	Phenology (days to maturity)	% Increase in grain yield	Reference
Wheat	Nutripriming with Zn (0.5 M)	Field	12.8 to 13.65	–	–	17.37–21.63	Rehman *et al.* (2018*b*)
	Nutripriming with Zn (0.5 M Zn) + *Pseudomonas* sp.	Field	10.61 to 16.88	–	–	18.94–27.27	Rehman *et al.* (2018*b*)
	Osmopriming (Se 0.1.25 mM)	Field	14.55	–	–	8.00	Idrees *et al.* (2018)
	Osmopriming (Se 1.25 mM)	Field	17.72	–	–	14.80	Idrees *et al.* (2018)
	Hydropriming	Field	3.46 to 3.17	–	–	3.85–5.30	Mustafa *et al.* (2018)
	Osmopriming	Field	5.58 to 6.61	–	–	7.01–8.37	Mustafa *et al.* (2018)
	Nutripriming (Mn)	Field	6.36 to 18.62	–	–	11.24–20.66	Ullah *et al.* (2018*a*)
	Osmopriming	Field	4.96	12.89	–	10.94	Ullah *et al.* (2018*b*)
	Osmopriming	Field	3.25	30 (LAI)	–	5.81	Haider *et al.* (2016)
	Osmopriming	Field	0.53	28.3	–	4.23	Haider *et al.* (2016)
	Hydropriming	Field	6.17 to 8.18	–	–	3.18–5.99	Nawaz *et al.* (2016)
	Hydropriming	Field	–1.19 to 7.39	–	–	1.98–8.67	Nawaz *et al.* (2016)
	Hydropriming	Field	1.46 to 9.39	–	–	5.48–7.23	Nawaz *et al.* (2016)
	Hydropriming	Field	2.49 to 3.18	–	–	0.28–13.51	Nawaz *et al.* (2016)
	Osmopriming	Field	2.42 to 7.71	–	–	13.54–17.61	Nawaz *et al.* (2016)
	Osmopriming	Field	–0.60 to 9	–	–	11.6–22.48	Nawaz *et al.* (2016)
	Osmopriming	Field	8.54 to 9.09	–	–	8.87–18.23	Nawaz *et al.* (2016)
	Osmopriming	Field	1.87 to 3.18	–	–	13.69–25.22	Nawaz *et al.* (2016)
	Osmopriming	Field	40.59	–	–	–	Afzal *et al.* (2013)
	Hormonal priming (kinetin)	Field	67.32	–	–	–	Afzal *et al.* (2013)
	Hormonal priming (ascorbate)	Field	74.25	–	–	–	Afzal *et al.* (2013)
	Hydropriming	Field	11.22	32.5 (LAI)	–	21.67	Jafar et al. (2012)
	Hormonal priming (ascorbate)	Field	19.52	55	–	38.42	Jafar *et al.* (2012)
	Osmopriming	Field	20.88	95	–	53.69	Jafar *et al.* (2012)
	Hormonal priming (SA)	Field	8.21	25	–	24.63	Jafar *et al.* (2012)
	Hormonal priming (kinetin)	Field	3.97	10	–	8.87	Jafar *et al.* (2012)
	Hydropriming	Field	9.5 to 11.84	–	Flowering: 1.75–2.82	8.72–11.64	Kant *et al.* (2004)
	Hormonal priming (IAA)	Field	15.8 to 19.30	–	–2.54 to 2.89	12.62–16.01	Kant *et al.* (2004)
	Osmopriming	Field	6.68 to 15.1	–	–1.32 to 2.72	10.42–13.11	Kant *et al.* (2004)
	Nutripriming ($ZnSO_4$)	Field	9.05 to 10.96	–	–1.75 to 2.84	8.42–8.53	Kant *et al.* (2004)
	Osmopriming	Field	7.15	–	–1.31 to 1.76	6.87–6.97	Kant *et al.* (2004)
Rice	Hydropriming	Field	4.8	–	–	5.8	Rehman *et al.* (2016)
	Nutripriming (B)	Field	12.26 to 13.65	–	–	10.58–24.63	Rehman *et al.* (2016)
	Hydropriming	Field	17.09 to 19.25	–	–	–6.56 to 1.56	Rehman *et al.* (2016)
	Nutripriming (B)	Field	20.56 to 26.02	–	–	15.69–27.05	Rehman *et al.* (2016)
	Hydropriming	Field	20.85 to 55.62	–	–	7.46–7.94	Rehman *et al.* (2016)
	Nutripriming (B)	Field	26.38 to 72.5	–	–	27.08	Rehman *et al.* (2016)
	Hydropriming	Field	4.92 to –5.14	–	–	4.41–14.98	Rehman *et al.* (2014*b*)
	Nutripriming (B)	Field	1.98 to 13.78	–	–	9.7–25.92	Rehman *et al.* (2014*b*)
	Hydropriming	Field	11.55 to 21.48	–	–	10.52–11.26	Rehman *et al.* (2014*b*)
	Nutripriming (B)	Field	14.2 to 28.82	–	–	21.05–25.5	Rehman *et al.* (2014*b*)
	Hydropriming	Field	23.41 to 69.86	–	–	–1.42 to –2.51	Rehman *et al.* (2014*b*)
	Nutripriming (B)	Field	28.90 to 36.98	–	–	12.57–20.39	Rehman *et al.* (2014*b*)
	Hydropriming	Farmer's field	–3.16	–3.6 (CGR)	–	–18.34	Rehman *et al.* (2011*b*)
	Osmopriming ($CaCl_2$)	Farmer's field	1.23	25.74	–	27.07	Rehman *et al.* (2011*b*)
	Osmopriming (KCl)	Farmer's field	–0.88	–33.06	–	0	Rehman *et al.* (2011*b*)
	Hydropriming	Field	16.51	2.14 (LAD)	–14.02	11.23	Farooq *et al.* (2007*a*)
	Osmopriming (KCl)	Field	20.05	3.57	–22.82	25.26	Farooq *et al.* (2007*a*)
	Osmopriming ($CaCl_2$)	Field	31.02	5.71	–22.89	31.58	Farooq *et al.* (2007*a*)
	Hormonal priming	Field	27	2.5	–17.55	19.65	Farooq *et al.* (2007*a*)
	Hydropriming	Field	12.84	–	–14.05	3.7	Farooq *et al.* (2006*c*)
	Osmopriming (KCl)	Field	12.67	–	–29.14	18.51	Farooq *et al.* (2006*c*)
	Osmopriming ($CaCl_2$)	Field	7.54	–	–23.53	14.81	Farooq *et al.* (2006*c*)
	Hormonal priming (ascorbate)	Field	10.10	–	–20.59	11.12	Farooq *et al.* (2006*c*)

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Table 3. (*continued*)

Crop	Seed priming type	Growing conditions	% Increase or decrease in tillering	Crop growth	Phenology (days to maturity)	% Increase in grain yield	Reference
Linola	Hydropriming	Field	5.69	–	–1.16	7.56	Rehman *et al*. (2014*a*)
	Osmopriming ($CaCl_2$)	Field	34.15	–	–2.81	39.49	Rehman *et al*. (2014*a*)
	Hormonal priming (MLE)	Field	26.01	–	–1.63	24.37	Rehman *et al*. (2014*a*)
Maize	Hydropriming	Field	–	22.2 (CGR)	–	29.11	Bakhtavar *et al*. (2015)
	Hydropriming	Field	–	12.6	–	34.11	Bakhtavar *et al*. (2015)
	Hormonal priming (MLE)	Field	–	22.4	–	37.7	Bakhtavar *et al*. (2015)
	Hormonal priming (MLE)	Field	–	13.6	–	28.83	Bakhtavar *et al*. (2015)
	Hydropriming	Field	–	1.52 (LAD)	–	4.72	Rehman *et al*. (2015*a*)
	Osmopriming ($CaCl_2$)	Field	–	10.75	–	17.95	Rehman *et al*. (2015*a*)
	Hormonal priming (MLE)	Field	–	15.01	–	38.74	Rehman *et al*. (2015*a*)
	Hormonal priming (SA)	Field	–	–	–	–	Rehman *et al*. (2015*a*)
	Nutripriming (Zn)	Field	–	3.29 (CGR)			Mohsin *et al*. (2014)
	Nutripriming (Zn)	Field	–	10.99 (CGR)	–	–	Mohsin *et al*. (2014)

Hence, it is concluded that seed priming is useful for improving crop growth and yield under stressed and non-stressed conditions.

Cropping system performance and resource use efficiency

Seed priming also improves resource use efficiency in terms of labour, water and the quality of harvested produce (Bakhtavar *et al*. 2015). Due to the rice–wheat edaphic conflict, post-rice wheat cultivation is delayed, which reduces wheat yield (Nasrullah *et al*. 2010; Nawaz *et al*. 2019). In this situation, seed priming helps decreases emergence time and achieves uniform stand, as well as increasing net profitability and water productivity of late-sown (Farooq *et al*. 2008*a*) and no-till wheat following direct seeding (Nawaz *et al*. 2016; Nadeem *et al*. 2019). Rehman *et al*. (2015*b*) reported improved water productivity in direct-seeded rice sown after priming with moringa water extract (3%) and irrigated with AWD. The application of micronutrients (Mn, B, Zn) through seed treatments can improve resource use efficiency in water-saving rice systems by reducing panicle sterility, enhancing photosynthetic performance and improving plant–water relationships (Rehman *et al*. 2014*b*, 2016). Seed priming with 10 mM Zn and 50 mM P improved Zn and P content in seeds, which not only affected seed germination and seedling growth under optimal and drought conditions, but also improved water use efficiency in barley (Ajouri *et al*. 2004). Seed priming of rice genotypes containing purine permease 1 (*PUP1*) genes and with different seed P content enhanced early seedling growth in high-P genotypes and stand establishment (seedling growth and germination) in low-P genotypes (Pame *et al*. 2015). The response was genotypic specific, and seed P content and seed priming can be combined with genetics to improve crop stand in P-deficient soils (Pame *et al*. 2015).

Role of seed priming in stress tolerance

Seed priming is a promising technology for combating abiotic stresses in crops and alleviating their detrimental effects (Lal *et al*. 2018). Young seedlings established from primed seeds are developmentally advanced in terms of their physiological state (Andreas *et al*. 2016). Seed priming stimulates the generation of signalling molecules or transcription factors in an inactive form, which activates defence responses upon exposure to a stressful environment (Bruce *et al*. 2007).

Plants grown from primed seeds and exposed to abiotic stresses (e.g. drought, heat, cold, heavy metals and salinity) have higher tolerance-related responses (e.g. protein stabilisation, activation of antioxidant systems, detoxification of ROS and molecular adjustment) than plants grown from unprimed seeds (Table 4). Activation of the molecular mechanism that involves translational modifications and transcriptional regulation (zinc finger proteins, myeloblastosis oncogene (*MYB*), dehydration responsive element binding (DREB)) strengthens the plant defence response and tolerance to the stressful environment (Fig. 3; Andreas *et al*. 2016). Seed priming improves crop growth and yield under optimum and suboptimum conditions, such as rising temperatures, drought and salinity (Kaya *et al*. 2006; Rehman *et al*. 2012; Farooq *et al*. 2013).

Thermal stress

Temperature fluctuations severely affect crop growth and yield (Afzal *et al*. 2008; Farooq *et al*. 2011*a*). In early spring crops, seedling emergence is delayed by low temperatures at sowing and later high-temperature effects during flowering or grain filling. Flowering and specifically grain filling are severely affected by high temperature, which shortens the growing period and results in poor assimilate translocation to seeds. High temperatures cause early leaf senescence, which slows the photosynthetic rate to adversely affect grain quality and quantity (Sharma-Natu *et al*. 2006; Hussain *et al*. 2008; Farooq *et al*. 2011*a*). High temperatures during the reproductive stage have an adverse effect on pollination and seed set, hampering grain filling and final grain yield (Afzal *et al*. 2008). Threshold temperatures are 38°C for corn at grain filling (Thompson 1986), 26°C for wheat after anthesis (Stone and Nicolas 1994), 35°C for pearl millet at the seedling stage (Ashraf and Hafeez 2004), 34°C for rice at seed set (Morita *et al*. 2005),

Table 4. Effects of seed priming treatments on tolerance against abiotic stresses in different field crops

ψ_w, water potential; AA, ascorbic acid; ABA, abscisic acid; B, boron; Chl, chlorophyll; GR, glutathione reductase; IAA, indole acetic acid; LPO, lipid peroxidation; MLE, moringa water extract; PEG, polyethylene glycol; RWC, relative water content; SA, salicylic acid; SNP, Sodium nitroprusside; SOD, superoxide dismutase; SWE, sorghum water extract; WUE, water use efficiency

Crop	Priming method	Type of stress	Growing conditions	Benefits gained	References
Wheat	Osmopriming with $CaCl_2$ (1.5%)	Drought stress	Field	Osmolyte accumulation; lower LPO; improved leaf area and tissue water status; higher grain yield	Tabassum *et al.* (2018*b*)
Wheat	Seed priming with benzyl aminopurine, SWE	Salt stress	Field	Accumulation of phenolics and total sugars; enhanced total protein, enzyme activity, Chl content and K^+ accumulation	Bajwa *et al.* (2018)
Wheat	Osmopriming with $CaCl_2$ (1.5%)	Salt stress	Greenhouse	Osmotic adjustment; better antioxidant defence system; reduced LPO; improved water relationships, osmolyte accumulation and yield	Tabassum *et al.* (2017)
Wheat	Osmopriming (AA)	Drought stress	Controlled conditions	Improved leaf emergence, Chl content, proline accumulation, plant water status	Farooq *et al.* (2013)
Wheat	Osmopriming with MLE diluted 30-fold	Salt stress	Greenhouse	Increased grain yield (18.5%)	Yasmeen *et al.* (2013)
Wheat	Hydropriming, osmopriming ($CaCl_2$), hormonal priming (kinetin, ascorbate)	Salt stress	Field	Decreased Na^+ and Cl^- uptake; increased K^+ in leaves; improved germination and grain yield	Afzal *et al.* (2013)
Wheat	Osmopriming with $CaCl_2$	Salt stress	Field	Increased germination, yield (by ~217%)	Jafar et al. (2012)
Wheat	Hydropriming, osmohardening (KCl, $CaCl_2$, ψ_w = 1.25 MPa), hardening	Chilling stress	Greenhouse	Uniform and earlier emergence; improved yield	Farooq *et al.* (2008*b*)
Wheat	Osmopriming (NaCl), auxin	Salt stress	Laboratory	Increased germination percentage, radicle and hypocotyl length, seedling fresh and dry weights	Akbari *et al.* (2007)
Wheat	Osmopriming with H_2O_2 (1, 40, 80 and 120 µM)	Salt stress	Greenhouse	Improved photosynthetic capacity, stomatal conductance and turgor maintenance; increased tissue levels of K^+, Ca^{2+}, NO^{3-}, PO_4^{3-} and activation of antioxidants	Wahid *et al.* (2007)
Rice	Hydropriming and osmopriming ($CaCl_2$)	Drought stress	Greenhouse	Improved stand establishment, accumulation of phenols, flavonoids, antioxidant systems	Hussain *et al.* (2017)
Rice	Osmopriming (Se; 50 µM) and hormonal priming (SA 100 mg L^{-1})	Chilling stress	Greenhouse	Enhanced starch metabolism, respiration rate; reduced LPO; improved antioxidative defence system	Hussain *et al.* (2016*b*)
Rice	Seed nutripriming with P (200 mM KH_2PO_4)	P deficiency	Greenhouse	Improved germination and seedling growth; enhanced P uptake	Pame *et al.* (2015)
Rice	Osmopriming with $CaCl_2$	Salt stress	Greenhouse	Improved germination, seedling length, Chl	Afzal *et al.* (2012*b*)
Rice	Biopriming with *Bacillus cereus*	Salt stress	–	Improved root and shoot growth, IAA and starch hydrolysis-related enzymes	Chakraborty *et al.* (2011)
Rice	Seed osmopriming with KCl (0.15, 0.30 and 0.45 M)	Submergence	Greenhouse	Improved seedling establishment, carbohydrate mobilisation; reduced LPO; enhanced antioxidant activity	Ella *et al.* (2011)
Rice	Osmopriming with SNP (100 mg L^{-1})	Drought stress	Greenhouse	Improved antioxidant enzymes, cellular membrane stability, photosynthesis and leaf water status by augmented synthesis of compatible solutes	Farooq *et al.* (2009*b*)
Maize	Nutripriming (4 mM $ZnSO_4$)	Salt stress	Greenhouse	Increased biomass and nutrient content, Na accumulation in shoots	Imran *et al.* (2018)

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Maize	Seed osmopriming (MLE 3%), hormonal priming with SA (50 mg L^{-1})	Chilling stress	Field	Earlier emergence and high vigorous growth; extended leaf area; improved yield	Rehman *et al*. (2015*a*)
Maize	Seed priming with Fe, Mn, B	Chilling stress	Field	Improved seedling growth, shoot micronutrient content, yield	Imran *et al*. (2013)
Maize	Osmopriming (MLE 3%)	Chilling stress	Laboratory	Maximised seedling growth; improved Chl content, amylase activity and total sugar content	Afzal *et al*. (2012*a*)
Maize	Osmopriming (SA 50, 100, 150 mg L^{-1})	Chilling stress	Greenhouse	Improved seedling growth, antioxidant activities, RWC; reduced membrane permeability	Farooq *et al*. (2008*b*)
Maize	Osmopriming (glycinebetaine 50, 100, 150 mg L^{-1})	Chilling stress	Greenhouse	Enhanced carbohydrate metabolism, seedling growth, antioxidant activities, RWC; reduced membrane permeability	Farooq *et al*. (2008*b*)
Maize	Osmopriming ($CaCl_2$ 100 mg L^{-1})	Chilling stress	Greenhouse	Enhanced carbohydrate metabolism, seedling growth, antioxidant activities, RWC; reduced membrane permeability	Farooq *et al*. (2008*b*)
Maize	Osmopriming (KCl)	Chilling stress	Controlled conditions	Improved germination, root and shoot length, activation of antioxidant enzymes, α-amylase activity; maintained tissue water content; reduced electrolyte leakage	Farooq *et al*. (2008*c*)
Maize	On-farm priming	Drought stress	Greenhouse	Reduced emergence time, optimum and ceiling temperatures for germination	Finch-Savage *et al*. (2004)
Sugarcane	Halopriming (100 mM NaCl)	Salt stress	–	Improved percentage and rate of germination, shoot length, shoot and root fresh weight	Patade *et al*. (2009)
Cotton (*Gossypium hirsutum* L.)	Hydropriming	Drought stress	Laboratory	Accelerated germination; reduced thermal time required for radicles to emerge; improved seed vigour	Casenave and Toselli (2007)
Cotton	On-farm priming	Drought stress	Laboratory	Higher emergence percentage; improved seedling growth	Murungu *et al*. (2003)
Barley	Osmopriming ($CaCl_2$) and biopriming (*Enterobacter* sp. FD-17)	Drought stress	Field	Improved leaf area, Chl content, phenolics accumulation, antioxidant activity, grain yield, grain mineral content	Tabassum *et al*. (2018*a*)
Barley	Seed nutripriming (10 mM Zn + 50 mM P)	P + Zn deficiency	Greenhouse	Improved growth, seed nutrient content, WUE	Ajouri *et al*. (2004)
Sunflower	Osmopriming (PEG-8000)	Drought stress	Field	Improved immunocytolocalisation of catalase, synthesis of catalase	Kibinza *et al*. (2011)
Sunflower	Hydropriming, osmopriming ($CaCl_2$), salinity imposed by NaCl	Salt stress	Laboratory	Increased germination percentage, root and shoot lengths	Kaya *et al*. (2006)
Canola (*Brassica napus* L.)	Hydropriming and osmopriming (KNO_3), salinity imposed by NaCl	Salt stress	Laboratory	Increased germination, root and shoot lengths, seedling growth; reduced mean germination time and unusual germination percentage	Omidi *et al*. (2009)
Fennel (*Foeniculum vulgare*)	SA (0, 0.25, 0.5 and 0.75 mM)	Salt stress	Laboratory	Increased seed stamina index, seedling fresh and dry weights (0, 0.25 mM)	Farahbakhsh (2012)

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Indian mustard (*Brassica juncea* L.)	Hydropriming, osmopriming ($CaCl_2$ and abscisic acid), salinity imposed by 150 mM NaCl	Salt stress	–	Increased seedling dry weight, Chl content, SOD and GR activity	Srivastava *et al.* (2010)
Mung bean	Osmopriming (NaCl 50 mM)	Salt stress	Laboratory	Improved growth; increased photosynthetic pigments in seedlings	Saha *et al.* (2010)
Quinoa (*Chenopodium quinoa*)	Osmopriming (H_2O_2 80 mM)	Drought stress	Greenhouse	Maintained turgor pressure; enhanced antioxidant activity, membrane stability, photosynthetic rate, ABA and antioxidant levels; reduced emergence time, osmotic adjustment	Iqbal *et al.* (2018)
Quinoa	Osmopriming (saponin 10%, 15%, 25%)	Salt stress	Greenhouse	Improved growth, plant water relations and gas exchange traits; reduced Na and high K uptake	Yang *et al.* (2018)
Quinoa	Osmopriming (paclobutrazol 20 mg L^{-1})	Salt stress	Greenhouse	Increase in the activity of antioxidant enzymes, enhanced germination	Waqas *et al.* (2017)
Indian mustard	Hydropriming, osmopriming ($CaCl_2$ and abscisic acid(, drought imposed by PEG-8000 20%	Drought stress	–	Increased seedling dry weight, Chl content, SOD and GR activity	Srivastava *et al.* (2010)
Canola	Hydropriming and osmopriming (KNO_3), drought imposed by PEG-6000	Drought stress	Laboratory	Increased germination, root and shoot lengths, seedling growth	Omidi *et al.* (2009)
Chickpea	Osmopriming ($CaCl_2$)	Chilling stress	Controlled climate chamber	Improved stand establishment, water relationships, photosynthesis, sugar metabolism, antioxidant enzyme activities, membrane stability	Farooq *et al.* (2017*c*)
Chickpea	Osmopriming (mannitol 4% or PEG; –0.5, –1.0, –1.5 and –2.0 MPa) or hydropriming	Drought stress	Laboratory	Faster and synchronised germination; decreased thermal time	Elkoca *et al.* (2007)
Soybean	Priming with KNO_3 and KH_2PO_4	Drought stress	Laboratory and field	Increased pod and grain numbers per plant (252–300%)	Ghassemi-Golezani *et al.* (2011)
Pea (*Pisum sativum* L.)	Biopriming with *Typha angustifolia*	Salt stress	Greenhouse	Better protection of membrane integrity; maintained highest value of osmotica (proline, total soluble sugars, K^+); improved photosynthetic pigments	Ghezal *et al.* (2016)

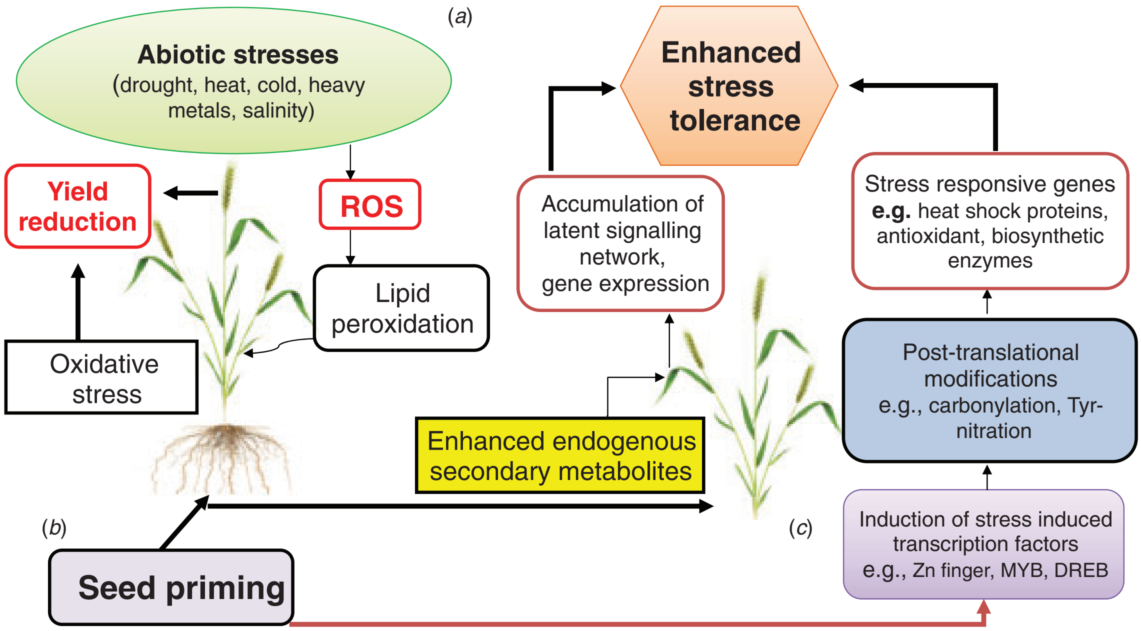

Fig. 3. Abiotic stress challenges and seed-priming-induced stress tolerance. (*a*) Upon exposure to abiotic stresses, reactive oxygen species (ROS) are produced, damaging plants due to the oxidative stress that induces multiple impairments, resulting in huge losses in economic yield. (*b*) Seed priming increases the level of secondary metabolites and activates the signalling network. (*c*) Improved molecular homeostasis with the induction of certain transcription factors (Zn finger proteins, myeloblastosis oncogene (MYB), dehydration responsive element binding (DREB)), post-translational modifications and enhanced activity of stress-responsive genes results in enhanced plant tolerance under stress.

45°C for cotton during the reproductive stage (Rehman *et al.* 2004), 29°C for brassica during flowering (Morrison and Stewart 2002) and 34°C for groundnut during pollen production (Vara *et al.* 2000). Seed quality is also affected by high-temperature stress (Hasan *et al.* 2013).

Seed priming with ascorbic acid (ASA; 200 mg L^{-1}) and SA (50 mg L^{-1}) improved growth in heat-stressed rice (Kata *et al.* 2014). Both ASA and SA positively affect various growth processes in plants, including seed germination, plant growth rate and photosynthesis, and detoxify the damaging effects of ROS (Cutt and Klessing 1992; Mahmood *et al.* 2010; Rafique *et al.* 2011; Farooq *et al.* 2013; Table 4). Application of allelopathic water extracts (moringa, sorghum, brassica and sunflower) through seed priming enhanced tolerance to high-temperature stress, reduced lipid peroxidation and malondialdehyde (MDA) content and improved chlorophyll content and water relationships in bread wheat (Hasegawa *et al.* 2000; Farooq *et al.* 2017*a*).

Seed priming with various growth promoters, including spermidine, proline, betaine, spermine and putrescine, has improved low-temperature tolerance in many crops under greenhouse conditions (Naidu and Williams 2004; Sasaki *et al.* 2005). Farooq *et al.* (2008*a*, 2008*b*) reported that seed priming with SA, $CaCl_2$ and glycine betaine increased chilling tolerance in maize. Seed priming reduces low temperature-induced oxidative stress by triggering the activity of antioxidants such as peroxidase, SOD and catalase. Moreover, it enhanced the accumulation of leaf free proline and glutathione in rice seedlings to impart tolerance to chilling stress (Hussain *et al.* 2016*b*). In addition, improved performance of rice crops under chilling stress has been attributed to priming-enhanced starch metabolism, decreased lipid peroxidation and high respiration rate (Hussain *et al.* 2016*b*). Xu *et al.* (2011) revealed that seed priming increased the tolerance of tobacco (*Nicotiana tabacum*) plants to low-temperature stress due to an improved antioxidant defence system. Seed priming with $CaCl_2$ alleviated the negative effect of low-temperature stress by increasing α-amylase activity and the photosynthetic rate, improving the antioxidant system and membrane stability and triggering the accumulation of leaf free proline in chickpea (Farooq *et al.* 2017*b*).

Salt stress

Salt stress results in poor emergence and seedling establishment in numerous crops, including maize, barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.), wheat, canola (*Brassica napus* L.) and rice (Afzal *et al.* 2006; Athar *et al.* 2009; Sattar *et al.* 2010). A sequence of biochemical, molecular, physiological and morphological changes may lower the maximum yield potential of crop plants exposed to salt stress (Wang *et al.* 2001). Seed priming improved stand establishment and yield performance in maize (Bakht *et al.* 2011), wheat (Table 4; Jafar et al. 2012), soybean (Arshi *et al.* 2010), sugarcane (Patade *et al.* 2009), sunflower (Bajehbaj 2010), chickpea (Kaur *et al.* 2005), alfalfa (Amooaghaie 2011), sorghum (Moradi and Younesi 2009), lettuce (Ouhibi *et al.* 2014) and rice (Afzal *et al.* 2012*b*) exposed to salt stress. Improved performance under salt stress by seed priming has been associated with enhanced activity of the antioxidant defence system (Younesi and Moradi 2014), osmotic adjustment, higher Na^+ and Cl^- concentrations in roots and elevated organic acid and sugar contents in leaves (Cayuela *et al*. 1996). Salt resistance has also been associated with Ca^{2+} and K^+ accumulation and reduced Na^+ accumulation contributing to osmoregulation from a build-up of organic solutes (Bajehbaj 2010). Nonetheless, seed priming is a promising and cost-effective approach to enhance seedling vigour and yield under salinity in various crops (Jafar et al. 2012; Table 4). However, the response will vary depending on genotype, osmoticum used and the extent of salt stress.

Drought stress

Drought stress obstructs seed germination and seedling emergence in several crops due to reduced water uptake and cell division (Farooq *et al*. 2009*a*). Seed priming has improved germination and seedling vigour in *Bromus* sp. and Egyptian clover (*Trifolium alexandrinum*; Rouhi *et al*. 2010; Tavili *et al*. 2011), chickpea (Elkoca *et al*. 2007), rice (Yuan-Yuan *et al*. 2010; Hussain *et al*. 2017) grasses (Rouhi *et al*. 2011), cotton seeds (Casenave and Toselli 2007), soybean (Ghassemi-Golezani *et al*. 2011) and wheat (Yin *et al*. 2013; Farooq *et al*. 2017*a*). The use of natural plant extracts (sorghum, brassica, sunflower and moringa) to induce drought resistance, particularly terminal drought, is promising and cost-effective (Cheema *et al*. 2013; Farooq *et al*. 2017*a*). In bread wheat, seed priming enhanced drought resistance during early seedling growth and the terminal reproductive period, which induced stress memory in the next generation of seeds, particularly under arid and semi-arid conditions (Tabassum *et al*. 2017).

Submergence

Poor crop establishment of direct-seeded rice in flood-prone areas is limited due to restricted coleoptile elongation and reduced carbohydrate metabolism under anaerobic conditions (Ismail *et al*. 2009). Seed priming improved stand establishment in rice varieties with or without *Sub1* gene. Introgression of a quantitative trait loci (QTL) in *Sub1* had no effect on seedling establishment percentage under flooding conditions, but increased it with seed priming (Sarkar 2012). Priming induced stress tolerance and improved performance in varieties containing QTL for stress tolerance, such as Swarna (containing *Sub1* for submergence tolerance) and IR74 (containing *Pup1* for high P uptake; Sarkar 2012). Ella *et al*. (2011) reported that, under low-oxygen stress, seed priming of rice with KCl reduced lipid peroxidation, improved SOD and catalase activity and hastened amylase activity and starch breakdown, resulting in better growth. Crop performance and survival under submergence were positively correlated with amylase activity and the extent of lipid peroxidation (Ella *et al*. 2011; Illangakoon *et al*. 2016). Under submerged conditions, seed priming of rice reduced mean germination time, resulting in uniform stand establishment (Ruan *et al*. 2002). Hussain *et al*. (2016*a*) reported that priming rice seeds with selenium (Se) and SA enhanced submergence tolerance and maintained uniform germination and vigorous seedling emergence. Moreover, the functioning of various genes (in response to oxidative stress) involved in carbohydrate metabolism and the metabolic processes of nitrogen compounds improved in primed relative to unprimed seeds.

Nutrient stress

Nutrient stress is a significant constraint for profitable and low-input crop production. Nutrient deficiency during initial growth stages retards seedling growth due to poor germination. In soils with low nutrient availability, seed priming with limited elements is often cited as the most attractive and economical option for improving crop performance (Adhikari and Rattan 2000; Slaton *et al*. 2001). For uniform emergence and stand establishment, seeds must contain ample nutrient reserves until the plant roots can extract nutrients from the soil. This approach is suitable for crops cultivated on soils with little capacity to provide nutrients for normal plant growth (Asher 1987). Emergence and crop performance of rice grown from seeds with high Zn concentrations yielded better in Zn-deficient soils than those with low food reserves (Hacisalihoglu and Kochian 2003; Tehrani *et al*. 2003). Priming mungbean seeds with P (0.01% and 0.02%) enhanced P uptake due to its mobilisation (Shah *et al*. 2012). Seeds with high P content have maximum potential to take up soil P and assimilation it towards shoot and grain than seeds with low P content (Zhu and Smith 2001). Seed priming with Zn (0.1 M $ZnSO_4$ or 0.5 M $ZnCl_2$) improved seedling growth and stand establishment in wheat (Rehman *et al*. 2015*c*) and rice (Prom-u-thai *et al*. 2012). Nutrient seed priming not only improved Zn and Mn content in seeds after priming, but also increased the translocation of seed reserves to growing seedlings and grain yield under nutrient-deficient conditions (Imran *et al*. 2015; Table 4). Low temperature usually disturbs nutrient uptake; nutrient translocation and seed priming can be a useful strategy for improving the performance of early sown maize under low root zone temperatures. For example, seed nutripriming with Fe or a combination of Zn and Mn under controlled and field conditions improved biomass and root length in maize, along with micronutrient status and grain yield (Imran *et al*. 2013; Table 4). Of the various methods of Se application (e.g. seed priming, seed coating, foliar spray and soil application), seed priming was the most effective and economical for producing the highest net return (Idrees *et al*. 2018). Similarly, priming with bioagents can maintain soil and crop health by increasing the supply or availability of primary nutrients to the host plant (Rakshit *et al*. 2015).

Biotic stress resistance

Weeds

Higher and synchronised emergence of primed seeds can ensure a vigorous and better crop stand (Basra *et al*. 2005) with rapid canopy development and offering direct-seeded crops a preliminary advantage over weeds (Clarke *et al*. 2001; Rehman *et al*. 2014*b*). Harris *et al*. (2002) reported that seed-primed rice seedlings competed more successfully with weeds. Clarke *et al*. (2001) opined that seed priming improved a crop's ability to compete with weeds; faster emergence and increased vigour in a primed stand are key factors for competing with weeds. Du and Tuong (2002) observed a positive effect of seed priming on weed suppression in direct-seeded rice at a low seeding rate. Seed priming significantly improved germination attributes, weed-suppressive ability and rice yields relative to unprimed seeds, with poor crop stands and weed competitiveness in the latter resulting in poor yield (Anwar *et al*. 2012). The reduction in weed dry matter due to priming ranged from 22% to 27% compared with the unprimed control, and weed-inflicted yield losses were curtailed by 10% (Juraimi *et al*. 2012).

Diseases and insect pests

Plants possess innate defence traits and have developed inducible defences against pathogens, insect pests and even higher plants (weeds), which lead to the regulation of gene expression and synthesis of defensive secondary metabolites and defence-related proteins (Dorantes-Acosta *et al*. 2012). However, plants can also be sensitised or primed for faster and more intense defence responses leading to enhanced resistance to biotic stresses. Collar rot (*Sclerotium rolfsii*) in chickpea, yellow mosaic virus in mung bean and downy mildew in pearl millet decrease with the use of hydroprimed seeds, whereas biopriming with *Trichoderma* controlled cowpea root rot pathogens. SA alone or in combination with magnesium nitrate ($Mg(NO_3)_2$) induced resistance in groundnut and mustard plants to *Alternaria alternata* and *Alternaria brassicae* (Mondal and Bose 2014). Indian farmers reported that primed chickpea suffered less damage from pod borers (Harris *et al*. 1999); similarly, damage from pod borers declined in primed versus unprimed chickpea in Bangladesh, but the difference was not statistically significant (Musa *et al*. 2001).

Biopriming integrates the biological and physiological aspects of disease control and has been used recently as an alternative method for controlling many seed- and soil-borne pathogens (El-Mougy and Abdel-Kader 2008; Nayaka *et al*. 2008; Rao *et al*. 2009). The colonisation of seedling roots with bioprimer microorganisms provokes broad-spectrum induced systematic resistance in plants and is fast emerging as a potential alternative to the use of chemical pesticides (Manjunatha *et al*. 2013). Biopriming seed treatments successfully controlled green bean root rots caused by *Fusarium solani*, *Rhizoctonia solani* and *F. oxysporum*, reducing root rot diseases by up to 73.9% and 68.5% before and after emergence respectively. Biopriming seeds to control root rot soil-borne plant pathogens as a substitute for chemical fungicides is possible without any risk to humans, animals or the environment (El-Mohamedy and Abd Alla 2013).

Priming and seed dormancy

Seed dormancy is a state of inhibited germination of seeds with viable embryos under conditions conducive to plant growth. There are various methods for breaking seed dormancy, including scarification (i.e. impaction, abrasion, acid scarification, heat and hot water treatment), stratification (cool temperature exposure to seeds) and priming. In lettuce, the embryo is enclosed within a 2- to 4-cell layer endosperm, and its cell walls primarily comprise galactomannan polysaccharides; hence, weakening the endosperm layer is a prerequisite for radicle protrusion, particularly at high temperatures, and endo-β-mannase is required, which needs ethylene for its activation. High temperature inhibits ethylene production in seeds and thus reduces the activity of endo-β-mannase, resulting in reduced germination (Cantiffe *et al*. 2000).

Seeds of oregano (*Origanum vulgare*) osmoprimed with polyethylene glycol (PEG), GA_3 or PEG plus chilling and soaking for 72 h resulted in dormancy breakdown (Farashah *et al*. 2011). At 35°C, imbibition of lettuce seeds (Dark Green Boston) in 1-aminocyclopropane-1-carboxylic acid (ACC; a precursor of ethylene) increased the activity of endo-β-mannose and improved germination. This suggests that osmopriming can be used as a substitute to ACC to break heat-induced dormancy. Osmopriming can overcome dormancy by releasing ethylene within the embryonic tissues encased by the seed coat and endosperm, which allows seeds to germinate (Nascimento *et al*. 2000).

Grain biofortification

Micronutrients are applied to crop plants through foliar spray, soil application or seed treatment. Each of these methods can provide nutrients in the required amounts, but the amount and cost of nutrients required for soil and foliar fertilisation are often prohibitive (Johnson *et al*. 2005; Rehman *et al*. 2012, 2014*b*, 2018*a*; Farooq *et al*. 2018). In nutripriming, seeds are soaked in a solution containing nutrients to start pregermination metabolic events without radical protrusion, after which seeds are dried closer to their original weight.

Seeds are not only major sources for human and animal foods, but are also a basic input material for the cultivation of most crops. The chemical composition of seeds determines their quality, including the concentration of micronutrients such as Zn, Cu, Fe (Waters and Sankaran 2011) and B (Rehman *et al*. 2014*b*). The ability of plants to accumulate and translocate these essential elements to edible and harvestable plant parts depends on factors such as agronomic management practices, soil and climatic factors and plant genotype (McLaughlin *et al*. 1999).

Worldwide, more than 2 billion people suffer from Fe, Zn and/or other micronutrient deficiencies (WHO 2016). The problem is most severe in low- and middle-income countries, especially Africa, where the estimated risk of micronutrient deficiencies is high for Ca (54% of the continental population), Zn (40%), Se (28%), I (19%) and Fe (5%) (Joy *et al*. 2014). Zn deficiency is a major concern for human nutrition, with ~2.7 billion people worldwide affected by Zn deficiency (Muller and Krawinkle 2005).

Biofortification of grains with Zn is a simple approach for treating Zn deficiency in humans (Bouis *et al*. 2011). Biofortification approaches such as genetic engineering, fertiliser application and conventional breeding have been reviewed extensively (Cakmak 2008). Zn fertilisation of wheat is not only a rapid solution to overcoming Zn deficiency, but also has the added benefit of improving grain yield (Cakmak 2009). Zn application is especially important in areas where low plant-available Zn in soils correlates with human Zn deficiency (Alloway 2009). Using the seed priming technique for Zn is an attractive option for grain biofortification; Zn application using this approach increased grain Zn concentration in maize (Harris *et al*. 2007), wheat (Rehman *et al*. 2018*b*; Table 5) and rice (Farooq *et al*. 2018;

Table 5. Effects of seed priming with micronutrients on grain yield and grain mineral enrichment in different field crops
$[Zn(Gln)_2]$, zinc glutamine; $[Zn(His)_2]$, zinc histidine; B, boron

Crop	Seed priming (source and rate of application)	Growing conditions and environment	% Yield improvement	% Increase in grain mineral content	References
		Zinc			
Wheat	Osmopriming with zinc sulfate (0.5 M)	Field	21.42	54.62	Ali *et al.* (2018)
	Hydropriming	Field	10.79	–	Tabassum *et al.* (2018*b*)
	Osmopriming (1.5% $CaCl_2$)	Field	13.96	–	Tabassum *et al.* (2018*b*)
	Seed priming with *Pseudomonas* sp. (Mn 12 M +Zn 0.5 M, 12 h)	Field	18–94 to 27.27	9	Rehman *et al.* (2018*a*)
	$[Zn(Gln)_2]$ (40 mg L^{-1})	Field	46		Seddigh *et al.* (2016)
	[Zn(His)2] (40 mg L^{-1})	Field	14	103	Seddigh *et al.* (2016)
	Osmopriming with $ZnSO_4$ (0.3% Zn, 10 h)	Field	14.00	12.00	Harris *et al.* (2008)
	Osmopriming with $ZnSO_4$ (0.3% Zn, 10 h)	On-farm and farmer's field	17.05	–	Harris *et al.* (2007)
	Osmopriming with $ZnSO_4$ (0.1%)	Field	34.87	–	Arif *et al.* (2007)
	Osmopriming with $ZnSO_4$ (0.004 M, 12 h)	Field	–	900	Johnson *et al.* (2005)
	Osmopriming with $ZnSO_4$ (0.1 M Zn)	Field	5.42	–	Nazir *et al.* (2000)
Rice	Seed priming with Zn (0.5 M, 24 h)	Field	31.25	26.67	Farooq *et al.* (2018)
	Osmopriming with $ZnSO_4$ (1% Zn)	–	14.57	–	Slaton *et al.* (2001)
	Osmopriming with $ZnSO_4$ (2.2% Zn)	–	17.92	–	Slaton *et al.* (2001)
	Osmopriming with $ZnSO_4$ (4.7% Zn)	–	28.25	–	Slaton *et al.* (2001)
Barley	Hydropriming	Field	6.46	–	Tabassum *et al.* (2018*a*)
	Osmopriming (1.5% $CaCl_2$)	Field	33.33	–	Tabassum *et al.* (2018*a*)
	Biopriming (*Enterobacter* sp. *FD-17*)	Field	27.21	–	Tabassum *et al.* (2018*a*)
	Osmopriming with $ZnSO_4$ (10 mg kg^{-1} Zn)	Controlled, incubator		708	Ajouri *et al.* (2004)
Chickpea	Osmopriming with $ZnSO_4$ (0.05% Zn, 10 h)	Field	19.00	29.00	Harris *et al.* (2008)
	Osmopriming with $ZnSO_4$ (0.004 M, 8 h)	Field	–	1066	Johnson *et al.* (2005)
	Osmopriming with $ZnSO_4$ (0.05%)	Field	36	–	Arif *et al.* (2007)
Maize	Osmopriming (0.5% Zn)	Field	10	33.63	Rasool *et al.* (2019)
	Osmopriming with $ZnSO_4$ (1% Zn, 16 h)	On farm and farmer's field	27.10	–	Harris *et al.* (2007)
	Nutripriming (4 mM Zn, $ZnSO_4 \cdot H_2O$ + 2.5 mM Mn, $MnSO_4$ for 24 h)	Growth chamber, controlled environment	15.00	50 Zn + 100 Mn	Imran *et al.* (2015)
	Nutripriming (1% Zn solution)	Field	5.61	13.27	Mohsin *et al.* (2014)
	Nutripriming (2% Zn solution)	Field	5.97	13.53	Mohsin *et al.* (2014)
Lentil	Osmopriming with $ZnSO_4$ (0.004 M, 12 h)	Field	–	55.56	Johnson *et al.* (2005)
		Boron			
Wheat	Osmopriming with H_3BO_3 (0.01 M)	Field	19.04	18.42	Ali *et al.* (2018)
	Seed priming with B (0.01 M B, 12 h)	Field	64	27.81	Iqbal *et al.* (2017)
	Seed priming with B (0.05 B, 12 h)	Field	20.66	37.59	Iqbal *et al.* (2017)
	Osmopriming with boric acid (0.008 M, 12 h)	Field	–	2122	Johnson *et al.* (2005)
Rice	Seed priming with B (0.1 mM)	Field	17.18	27.5	Rehman *et al.* (2016)
	Seed priming with B (0.1 mM)	Field	19.18	29.6	Rehman *et al.* (2014*b*)
	Seed priming with B (0.001 and 0.01 B %, 24 h)	Soil filled pots	–	33–47	Rehman *et al.* (2012)
	Osmopriming with H_3BO_3 (0.008 M, 36 h)	Field	–	700	Johnson *et al.* (2005)
Maize	Osmopriming (0.01% B)	Field	7.17	35.31	Rasool *et al.* (2019)
Lentil	Osmopriming with H_3BO_3 (0.008 M, 12 h)	Field	–	1566	Johnson *et al.* (2005)
Chickpea	Osmopriming with H_3BO_3 (0.008 M, 8 h)	Field	–	900	Johnson *et al.* (2005)
		Cobalt			
Common bean	Seed soaking in $Co(NO_3)_2$ (1 mg L^{-1}, 1 h)	Field	52.50	334.09	Mohandas 1985)
	Seed soaking in $Co(NO_3)_2$ (2 mg L^{-1}, 1 h)	Field	5.04	147.73	Mohandas 1985)
Oats	Seed soaking with $CoSO_4$ (0.001%, 1 h)	Field	11.17	–	Saric and Saciragic (1969)
		Manganese			
Wheat	Osmopriming with $MnSO_4$ (0.1 M)	Field	19.04	48.54	Ali *et al.* (2018)
	Seed priming with Mn (0.1 M, 12 h)	Field	11.24 to 20.66	24.31 to 61.22	Ullah *et al.* (2018*a*)
	Seed priming with $MnSO_4$ (0.1 M, 12 H)	Field	16.53	–	Nazir *et al.* (2000)
Maize	Osmopriming (0.01% Mn)	Field	6.46	31.62	Rasool *et al.* (2019)
	Nutripriming (2.5 mM Mn, $MnSO_4$, 24 h)	Growth chamber, controlled environment	15.00	100	Imran *et al.* (2015)
	Nutripriming (2.5 mM Mn, $MnSO_4$, 24 h)	Field	14.60	800	Imran *et al.* (2013)

Table 5). Application of Zn with polyglycerol polyricinoleate improved Zn bioavailability and grain yield in wheat (Rehman *et al*. 2018*b*; Table 5). Similarly, manganese (Mn) application using seed priming improved grain biofortification and yield in wheat (Ullah *et al*. 2018*a*; Table 5).

In addition to grain micronutrient concentrations, seed priming with respective micronutrients improved grain nutritional components, such as protein content (Seddigh *et al*. 2016; Rehman *et al*. 2018*b*), and reduced antinutritional factors, such as Cd and phytate in grain (Slamet-Loedin *et al*. 2015).

Bases of priming-induced benefits

Physiological and biochemical bases of priming-induced benefits

Seed priming triggers cell cycle-related processes and increases peroxidase and SOD activity, which increases respiratory activity and ultimately improves seed germination and vigour (Fig. 4). Seed priming stimulated nuclear DNA synthesis in cells of maize radicles, as well as peroxidase concentrations and seed protein content. During priming, metabolic activity converts stored reserves into compounds necessary for seed germination (Fig. 4; Gallardo *et al*. 2001). Under salt stress, priming treatments significantly enhanced catalase and SOD activity, as well as proline content, and reduced MDA accumulation and electrolyte leakage. Enhanced resistance to abiotic stresses through application of compatible solutes via seed priming is due to osmotic adjustment under salinity (Hare *et al*. 1998; Hasegawa *et al*. 2000), ionic homeostasis and hormone regulation in chilling-induced salt stress (Iqbal and Ashraf 2010) and enhanced antioxidant activity and carbohydrate mobilisation to growing coleoptiles under flooded conditions (Ella *et al*. 2011). Similarly, magneto-induced priming benefits have been related to enhanced ascorbate content, enzyme activity, protein content and the regulation of metabolic pathways. The physiological and biochemical bases underlying the effects of the priming techniques need further elucidation (Mamat *et al*. 2005; Yinan *et al*. 2005).

At the biochemical level, UVB radiation increased total soluble phenols and the activity of enzymes such as tyrosine ammonia lyase and phenylalanine ammonia lyase in mung bean (Shaukat *et al*. 2013). Moreover, priming with fish protein hydrolysates and oregano extract in maize increased antioxidant activity and phenolic content (29% and 22% respectively) and reduced lipid peroxidation activity (Randhir and Shetty 2005). Exposure of wheat seeds to UVA and UVB radiation protected wheat plants against oxidative damage by decreasing lipid peroxidation and hydrogen and promoting the activity of antioxidants such as peroxidase, catalase and SOD (Abu-Elsaoud and Hassan 2016). Plausibly, improved germination and seedling performance with magneto-priming are ascribed to the activity of α-amylase, dehydrogenase and protease (Fig. 4; Vashisth and Nagarajan 2010; Anand *et al*. 2012). Plants raised after magneto-priming perceive signals mediated by blue light photoreceptors (cryptochromes; Ahmad *et al*. 2007); however, this aspect of magnetobiology needs further exploration, including probable genotoxic side effects (Ghodbane *et al*. 2013).

Imbibition phase

During imbibition, water is imbibed by the seed due to a water potential gradient between hydration medium and dry seeds. During this phase, little metabolic activity occurs in viable seeds.

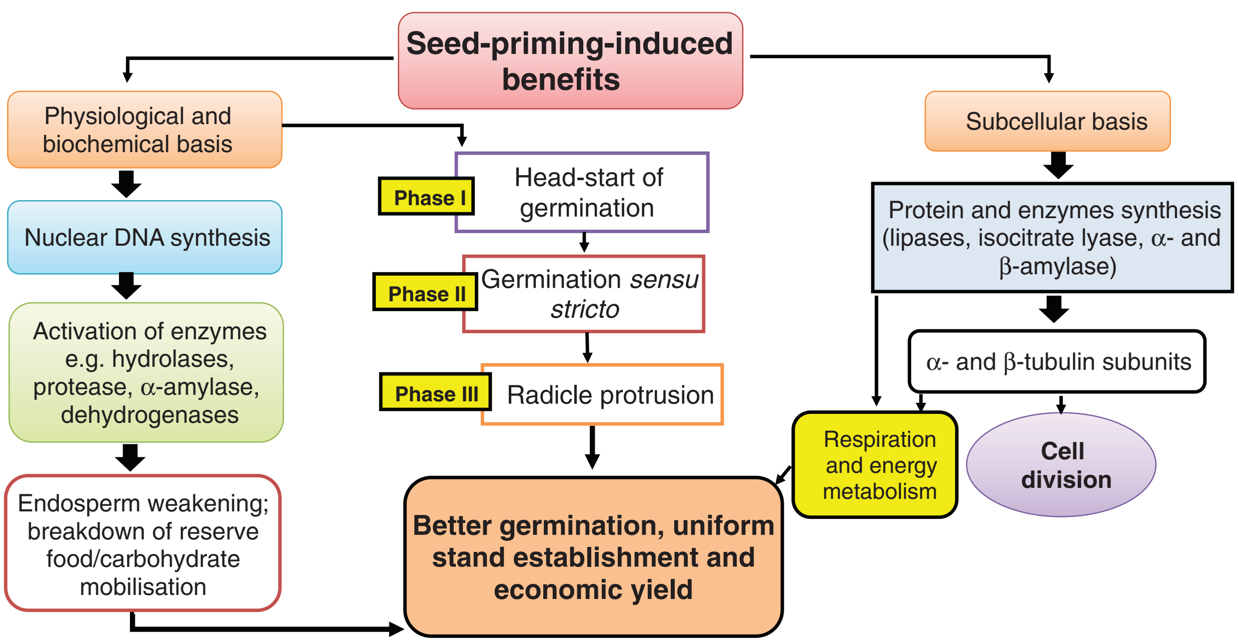

Fig. 4. Seed priming and its physiological, biochemical and subcellular-induced benefits that help improve crop germination, stand establishment and economic yield.

Lag phase

In the lag phase, minimal water imbibition takes place, such that little change occurs in seed fresh weight. In this phase, extensive metabolic activities take place, and the stored seed reserves (lipids, fat, carbohydrates and proteins) are converted into essential compounds for seed germination.

Radical protrusion phase

During this phase seeds take up water very rapidly, and radicle protrusion occurs. Seeds usually exhibit desiccation tolerance in the first two phases of germination, but become intolerant in the final stage. All three stages are controlled by the availability of water to seeds (Taylor *et al*. 1998). During priming, seed metabolic activities renew reserves for seed germination. Saha *et al*. (2010) reported that an increase in enzyme activity with priming neutralises the lipid peroxidation effect. During priming, α-amylase is activated (Lee and Kim 2000), and there is a direct relationship between α-amylase and metabolic activity; seed metabolic activities increase as α-amylase activity increases and, ultimately, seed vigour increases. Priming with 30% PEG in wild rye for 24 h increased the activity of peroxidase and SOD, which increased respiratory activity, seed vigour and germination. Seed priming has been used to increase germination percentage, reduce seedling germination time and improve stand establishment and crop yield (Basra *et al*. 2005). Pigeon pea (*Cajanus cajan* L.) seeds treated with KNO_3 and $CaC1_2$ had improved soluble sugar, protein and amino acid content during germination under stress conditions (Bakht *et al*. 2011).

Subcellular basis of priming-induced benefits

Protein and enzyme synthesis during priming

Priming induces the activation and synthesis of enzymes required to breakdown and mobilise stored food reserves, most of which occur during germination. The enzymes responsible for the mobilisation of carbohydrates (e.g. α- and β-amylase) and lipids (e.g. isocitrate lyase, lipases) are activated during seed priming (Fu *et al*. 1988). Seed priming with NaCl enhanced α-amylase activity in chickpea (Kamithi *et al*. 2016). Priming is also involved in the synthesis of catalase, which is involved in seed recovery (Kibinza *et al*. 2011). The α- and β-tubulin subunits, constituents of microtubules involved in cell division and maintenance of the cytoskeleton, are abundant during seed priming. The catalase isoform is a protein that increases during hydropriming. Hydropriming induces oxidative stress, resulting in the production of ROS, and catalase, a free radical-scavenging enzyme, is synthesised to minimise cell damage during priming. The activity of SOD, a key enzyme quenching free radicals, also increases during seed priming. The increased levels of free radical-scavenging enzymes during priming due to oxidative stress protect cell membranes from naturally occurring lipid peroxidation (Bailly *et al*. 2000; Vari *et al*. 2003). Low molecular weight heat shock proteins (LMW HSPs) significantly increase during osmopriming and have a molecular chaperone activity (Lee *et al*. 1995). During osmopriming, LMW HSPs maintain proper folding of other proteins, prevent aggregation and protect against protein damage by natural aging. In addition, L-isoaspartyl protein methyltransferase, an enzyme responsible for repairing age-induced damage to cellular proteins, increases with priming (Kester *et al*. 1997). Priming of beet (*B. vulgaris* L.) seeds improved solubilisation of the β-subunit of the 11-S globulin fraction of a seed storage protein (Bourgne *et al*. 2000). Except for the expression of the *LsNCED4* gene responsible for 9-*cis*-epoxycarotenoid dioxygenase activity, regulating the abscisic acid biosynthesis pathway is temperature dependent and reversed (Schwember and Bradford 2011). Priming induces the expression of genes related to stress tolerance, including *CaWRKY30*, *PROX1* and *Osmotin* for osmotic adjustment, Cu/Zn-SOD (*SOD*) for antioxidants and *CAH* for the phenylpropanoid pathway. Enhanced levels of plant growth hormones (IAA, abscisic acid, cytokinin) following osmopriming or biopriming of seeds of *Bacillus* spp. have been reported (Patade *et al*. 2012). Recently, Hussain *et al*. (2017) showed that a common basis exists for seed priming-induced tolerance to submergence, carbohydrate metabolism and oxidative stress tolerance. Nonetheless, application of proteomics or other molecular tools can help identify the complex pathways involved in seed vigour, and changes in the expression of proteins during commercial priming can accelerate the development and delivery of primed seeds and their tolerance to abiotic stresses.

Effects of priming on protein-synthesising machinery

Priming enhances protein synthesis by improving the proper functioning of protein-synthesising machinery. By enhancing rRNA synthesis, priming improves the integrity of ribosomes (Coolbear *et al*. 1990). During osmopriming, levels of genes involved in encoding the components of translation machinery (i.e. ribosomal subunits, initiation and elongation factors) increase, allowing the proper functioning of protein-synthesising machinery.

DNA repair during priming

Maintenance of DNA integrity is achieved through the repair of natural damage, which is important for generating an error-free template for transcription and replication. Thornton *et al*. (1993) reported that damage to DNA that occurs during seed aging is repaired during aerated hydration treatments, and prereplicative repair of damaged DNA also occurs during hydration treatments.

Priming and the cell cycle

Seed priming enhances DNA replication and advances the cell cycle from the G_1 to G_2 phase. To obtain maximum benefits from priming, the process is stopped just before radicle emergence or stage III of water uptake (Özbingöl *et al*. 1999). Osmopriming improves germination, which is linked to an increase in 4C nuclear DNA. Powell *et al*. (2000) reported an increase in the fraction of nuclear DNA in the 4C state following aerated hydration treatment. In addition, a twofold increase in total genomic DNA content was reported when corn seed was hydroprimed (Thasni 2003).

Levels of tubulin, a cytoskeletal protein required for the formation of cortical microtubules, increase during hydropriming. After redrying, f-tubulin can be seen as clusters or granules, which may be due to the sensitivity of microtubules to dehydration that are partly depolymerised after drying. However, the amount of soluble f-tubulin present after redrying is relatively high because microtubules exist in equilibrium between polymerised microtubules and soluble tubulin subunits (Powell *et al*. 2000). The cell cycle is arrested at the G_2 phase, allowing cell synchronisation during priming. Cell division and mitotic events occur earlier in embryos of primed seeds upon subsequent imbibition in water relative to controls. Thus, the resulting preactivation of the cell cycle is one mechanism by which priming induces better performance relative to untreated seeds. Regulation of the cell cycle by priming occurs through regulation of the activity of cell cycle proteins such as cyclin-dependent protein kinases, proliferating-cell nuclear antigens (PCNA) and cyclins. When maize seeds were imbibed in water in the presence of benzyladenine, the amount of PCNA increased relative to the control, and increased amounts of PCNA were associated with an acceleration of the passage of cells from the G_1 to G_2 phase of the cell cycle (Sanchez *et al*. 2005). Moreover, low-dose gamma irradiation had a triggering effect on enzyme activity, as well as protein and nucleic acid preparation in seeds. These metabolic changes result in earlier emergence and better performance of plant species under various environmental conditions (Sjodin 1962).

Effects of priming on respiration and energy metabolism

Osmopriming with PEG abruptly increased the energy charge (ATP and ATP/ADP ratio) even after drying. During subsequent imbibition, primed seeds had higher energy metabolism than unprimed seeds, making them more vigorous. A high ATP content of the redried primed seed is maintained for at least 4–6 months during storage at 20°C, and the maximum benefit of priming occurs when conducted in an atmosphere containing >10% oxygen. Proteins, including tubulin and the subunit of 12S seed storage protein, increased upon seed priming (hydropriming, PEG osmopriming; Gallardo *et al*. 2001). Furthermore, sugar (reducing and non-reducing) content increased significantly in primed seeds relative to non-primed seeds (Lamichaney *et al*. 2018), which improved germination and plant growth. Seed priming enhanced starch metabolism and increased α-amylase activity to hydrolyse starch into soluble sugars for seed respiration and better growth (Farooq *et al*. 2006*e*). Respiration is essential for effective priming and, in the presence of a respiratory inhibitor such as NaN_3 at higher concentrations, priming treatments are ineffective (Corbineau *et al*. 2000). Hussain *et al*. (2016*b*) reported that seed priming rapidly increased the respiration rate and ATP production to trigger germination and seedling growth in rice. Seed respiratory activity is a good indicator of the activation of germinative metabolic activity (Patanè *et al*. 2006). Seeds of wild rye (*Elymus chinensis* L.) and carrot (*Daucus carota*) primed with 30% PEG and hydropriming showed better respiration activity than non-primed seeds (Ji *et al*. 2002; Nascimento *et al*. 2013).

Cost-benefit analysis

Economic feasibility of priming techniques is associated with the type of chemical used for seed soaking, ease of handling primed seeds, yield and net field benefits in terms of high-cost input to output ratio. Very few studies have discussed the implication of priming technology in terms of the benefit to cost ratio. Among the priming techniques, the highest net field benefits have been observed for osmopriming and hormonal priming, followed by nutripriming and hydropriming (Table 6). However, the cost-benefit ratio varied among priming techniques, with the highest percentage increase observed for hormonal priming followed by osmopriming, hydropriming and nutripriming (Table 6).

Adoption by farmers

Seed priming is a cost-effective technique that is used in numerous countries, including Pakistan, Nepal, Australia, China, India, Bangladesh and Zimbabwe. More than 1000 trials have been conducted on a variety of crops (Singh and Gill 1988; Harris *et al*. 2001; Farooq *et al*. 2006*a*, 2006*b*, 2006*c*; Moradi and Younesi 2009; Jafar et al. 2012; Hussain *et al*. 2013; Table 7) to evaluate the performance of various priming techniques. In 1996, 53 growers in tribal areas of Gujarat, Madhya Pradesh and Rajasthan in India tested maize seed priming during the Kharif season (Harris *et al*. 1999). Most farmers experienced more vigorous crop growth, earlier flowering and maturity, bigger cobs and higher yields from primed than unprimed seeds. A subset of 35 trials showed an average increase in cob weight of approximately 6% (Harris *et al*. 2001). Various farmers reported better and vigorous stand establishment, improved drought tolerance, earlier flowering (~7–10 days) and maturity (~8–10 days) from primed compared with unprimed seeds (Harris *et al*. 1999).

Priming treatments at different sites in farmer-managed trials improved maize grain yields by 105–182 kg ha^{-1} relative to non-primed maize trials. In 1999–2000 and 2000–01, economic maize yields increased by 14% and 18%, respectively (Clarke *et al*. 2001). Primed maize seeds produced taller plants that flowered and matured earlier than plants from non-primed seeds. Water-primed maize seeds increased total biomass by 10.81 t ha^{-1}, straw yield by 7.49 t ha^{-1}, cob yield by 3.32 t ha^{-1} and grain yield by 2.74 t ha^{-1} relative to non-primed treatments across six farmer-implemented trials (Harris *et al*. 2007). In 1997–98, 40 farmers in Zimbabwe primed sorghum seed, with most experiencing accelerated emergence and earlier flowering and maturity than seen for plants from non-primed seeds (Harris *et al*. 2001).

Because of its numerous benefits, seed priming is now used in many countries to improve crop growth and yields under optimal and suboptimal conditions.

Challenges

The benefits of seed priming are significant if maintained during storage after priming for a long period. Some studies have examined the longevity of seeds primed with different priming agents, and these are discussed below.

Longevity of primed seeds

Post-priming benefits can vary with seed priming type, redrying, seed lot vigour and storage conditions, including temperature, relative humidity and oxygen. Aerated hydration treatments decreased the longevity of high-vigour okra seeds and

Table 6. Effects of seed priming treatments on economic benefits in different field crops

AWD, alternate wetting and drying; B, boron; DSR, direct-seeded rice; MLE, moringa water extract; PEG, polyethylene glycol; PTR, puddled transplanted rice; SA, salicylic acid; SRI, system of rice intensification

Crop	Seed priming type	Production system	Environment type	% Increase in benefit : cost ratio over control	References
Wheat	Hydropriming	Conventional tillage	Normal	1.80	Muzaffar *et al*. (2019)
	Hydropriming	Conventional tillage	Normal	7.64	Muzaffar *et al*. (2019)
	Osmopriming	Conventional tillage	Normal	9.55	Muzaffar *et al*. (2019)
	Osmopriming	Happy seeder	Normal	1.43	Muzaffar *et al*. (2019)
	Hydropriming	Happy seeder	Normal	3.61	Muzaffar *et al*. (2019)
	Hydropriming	Happy seeder	Normal	2.39	Muzaffar *et al*. (2019)
	Osmopriming	Happy seeder	Normal	7.17	Muzaffar *et al*. (2019)
	Hydropriming	Turbo seeder	Normal	5.63	Muzaffar *et al*. (2019)
	Hydropriming	Turbo seeder	Normal	1.80	Muzaffar *et al*. (2019)
	Osmopriming	Conventional tillage	Normal	–	Idrees *et al*. (2018)
	Osmopriming	Conventional tillage	Normal	–	Idrees *et al*. (2018)
	Nutripriming (Zn)	Conventional tillage	Normal	4.46–11.80	Ali *et al*. (2018)
	Nutripriming (B)	Conventional tillage	Normal	10.05–14.04	Ali *et al*. (2018)
	Nutripriming (Mn)	Conventional tillage	Normal	1.67–6.74	Ali *et al*. (2018)
	Hydropriming	No tillage	Normal	5.34	Mustafa *et al*. (2018)
	Osmopriming	No tillage	Normal	–2.00	Mustafa *et al*. (2018)
	Hydropriming	Conventional tillage	Normal	4.79	Mustafa *et al*. (2018)
	Osmopriming	Conventional tillage	Normal	0	Mustafa *et al*. (2018)
	Osmopriming	Conventional tillage	Normal	4.38–5.88	Farooq *et al*. (2017*b*)
	Osmopriming	Conventional tillage	Early drought	3.43–13.8	Farooq *et al*. (2017*b*)
	Osmopriming	Conventional tillage	Terminal drought	32–41	Farooq *et al*. (2017*b*)
	Nutripriming (Mn)	Conventional tillage	Normal	5.02–6.62	Ullah *et al*. (2018*a*)
	Nutripriming (Mn)	Conventional tillage	Normal	14.05	Ullah *et al*. (2018*a*)
	Osmopriming	Conventional tillage	Normal	–	Hussain *et al*. (2016*c*)
	Osmopriming	Conventional tillage	Early drought	–	Hussain *et al*. (2016*c*)
	Hydropriming	DSR–plough till wheat	Normal	3.49	Nawaz *et al*. (2016)
	Osmopriming	DSR–plough till wheat	Normal	6.35	Nawaz *et al*. (2016)
	Hydropriming	PTR–plough till wheat	Normal	5.38	Nawaz *et al*. (2016)
	Osmopriming	PTR–plough till wheat	Normal	5.99	Nawaz *et al*. (2016)
	Hydropriming	DSR–no-till wheat	Normal	3.2	Nawaz *et al*. (2016)
	Osmopriming	DSR–no-till wheat	Normal	4.28	Nawaz *et al*. (2016)
	Hydropriming	PTR–no-till wheat	Normal	3.01	Nawaz *et al*. (2016)
	Osmopriming	PTR–no-till wheat	Normal	5.42	Nawaz *et al*. (2016)
	Osmopriming	Conventional tillage	Normal	22.8	Farooq *et al*. (2015*b*)
	Osmopriming	Conventional tillage	Terminal drought	24.18	Farooq *et al*. (2015*b*)
	Hydropriming	Conventional tillage	Salinity	12.5	Jafar *et al*. (2012)
	Osmopriming	Conventional tillage	Salinity	35.62	Jafar *et al*. (2012)
	Hormonal priming	Conventional tillage	Salinity	15.23	Jafar *et al*. (2012)
	On-farm priming (0.5% $ZnSO_4$)	Conventional tillage	Semiarid conditions	75	Harris *et al*. (2008)
Rice	Nutripriming (Zn)	DSR	Field capacity	6.00	Farooq *et al*. (2018)
	Nutripriming (Zn)	Flooded rice	Flooding	15.38	Farooq *et al*. (2018)
	Nutripriming (Zn)	DSR	Field capacity	18.18	Farooq *et al*. (2018)
	Nutripriming (Zn)	Flooded rice	Flooding	15.38	Farooq *et al*. (2018)
	Nutripriming (B	DSR	Field capacity	12.63	Rehman *et al*. (2016)
	Hydropriming	AWD	Dry-wet	9.78	Rehman *et al*. (2016)
	Nutripriming (B)	AWD	Dry-wet	11.40	Rehman *et al*. (2016)
	Hydropriming	Flooded rice	Flooding	5.82	Rehman *et al*. (2016)
	Nutripriming (B)	Flooded rice	Flooding	21.36	Rehman *et al*. (2016)
	Hydropriming	DSR	Field capacity	7.48	Rehman *et al*. (2014*b*)
	Nutripriming (B)	DSR	Field capacity	16.82	Rehman *et al*. (2014*b*)
	Hydropriming	AWD	Dry-wet	44.56	Rehman *et al*. (2014*b*)
	Nutripriming (B)	AWD	Dry-wet	57.60	Rehman *et al*. (2014*b*)
	Hydropriming	Flooded rice	Flooding	–2.3	Rehman *et al*. (2014*b*)
	Nutripriming (B)	Flooded rice	Flooding	13.7	Rehman *et al*. (2014*b*)
	Osmopriming ($CaCl_2$)	DSR-SRI	Saturated	5.88	Ahmad *et al*. (2013)
	Hydropriming	DSR-SRI	Saturated	4.07	Ahmad *et al*. (2013)
Maize	Hydropriming	Ridge cultivation	Low temperature	16.92	Bakhtavar *et al*. (2015)
	Hydropriming	Ridge cultivation	Normal	25.83	Bakhtavar *et al*. (2015)
	Osmopriming (MLE)	Ridge cultivation	Normal	24.61	Bakhtavar *et al*. (2015)
	Osmopriming (MLE)	Ridge cultivation	Low temperature	33.34	Bakhtavar *et al*. (2015)

(*continued next page*)

Table 6. (*continued*)

Crop	Seed priming type	Production system	Environment type	% Increase in benefit : cost ratio over control	References
	Hydropriming	Ridge cultivation	Normal	6.16	Rehman *et al.* (2015*a*)
	Hydropriming	Ridge cultivation	Low temperature	3.94	Rehman *et al.* (2015*a*)
	Osmopriming ($CaCl_2$)	Ridge cultivation	Normal	9.58	Rehman *et al.* (2015*a*)
	Osmopriming ($CaCl_2$)	Ridge cultivation	Low temperature	3.94	Rehman *et al.* (2015*a*)
	Osmopriming (MLE)	Ridge cultivation	Normal	50.46	Rehman *et al.* (2015*a*)
	Osmopriming (MLE)	Ridge cultivation	Low temperature	62.09	Rehman *et al.* (2015*a*)
	Hormonal priming (SA)	Ridge cultivation	Normal	30.82	Rehman *et al.* (2015*a*)
	Hormonal priming (SA)	Ridge cultivation	Low temperature	33.99	Rehman *et al.* (2015*a*)
Chickpea	On-farm priming	Dibbling	Semiarid conditions	18.33	Farooq *et al.* (2019)
	Hydropriming	Dibbling	Semiarid conditions	16.11	Farooq *et al.* (2019)
	Osmopriming	Dibbling	Semiarid conditions	21.11	Farooq *et al.* (2019)
	On-farm priming (0.5% $ZnSO_4$)	Dibbling	Semiarid conditions	780	Harris *et al.* (2008)
Soybean	Osmopriming with PEG	Dibbling	Semiarid conditions	–	Arif *et al.* (2008)
Sunflower	Osmopriming with 0.5% KNO_3 and 0.1% NaCl	Dibbling	Semiarid conditions	–	Hussain *et al.* (2006)
Cowpea	Borax (100 mg kg^{-1} seed)	Dibbling	Normal	–	Masuthi *et al.* (2009)
Linola	Hydropriming	Conventional tillage	Normal	4.03	Irshad *et al.* (2016)

Table 7. Crops in developing countries accruing benefits from seed priming treatments

Crop	Experimental conditions	Country	References
Wheat	Field	India	Kant *et al.* (2004), Harris *et al.* (2001)
	Farmer's field	Nepal	Harris *et al.* (2001)
	Farmer's field	Pakistan	Harris *et al.* (2001)
	Field	Pakistan	Farooq *et al.* (2008*a*)
	Farmer's field	Pakistan	Jafar *et al.* (2012)
	Field	Pakistan	Hussain *et al.* (2013)
	Field	Pakistan	Farooq *et al.* (2015*b*)
	Field	Pakistan	Hussain *et al.* (2016*c*)
	Field	Pakistan	Farooq *et al.* (2017*b*)
Rice	Farmer's field	India	Harris *et al.* 1999)
	Farmer's field	Sierra Leone	Harris (2003)
	Farmer's field	Nigeria	Harris (2003)
	Farmer's field	Ghana	Harris *et al.* (2002)
	Farmer's field	Cameroon	Harris *et al.* (2002)
	Field	Pakistan	Farooq *et al.* (2006*c*, 2007*a*, 2007*b*)
	Farmer's field	Pakistan	Rehman *et al.* (2011*b*, 2012)
	Field	Pakistan	Rehman *et al.* (2015*c*)
	Field	Pakistan	Ahmad *et al.* (2013)
Maize	Farmer's field	India	Harris *et al.* 1999)
	Farmer's field	Pakistan	Harris *et al.* (2007)
	Field	Pakistan	Bakht *et al.* (2010)
	Field	Pakistan	Rehman *et al.* (2015*a*)
	Field	Pakistan	Bakhtavar *et al.* (2015)
Sorghum	Farmer's field	Botswana	Harris (1996)
	Farmer's field	Zimbabwe	Chivasa *et al.* (1998)
Chickpea	Farmer's field	India	Harris *et al.* (1999)
	Farmer's field	Bangladesh	Musa *et al.* (2001)
	Farmer's field	Pakistan	Harris *et al.* (2008)
	Field	Pakistan	Farooq *et al.* (2019)
Finger millet (*Eleusine coracana*)	Farmer's field	India	Kumar *et al.* (2002)
Cowpea	Farmer's field	Senegal	Masuthi *et al.* (2009)
Soybean	Field	Pakistan	Arif *et al.* (2008)
	Field	Iran	Ghassemi-Golezani *et al.* (2011)
Linola	Field	Pakistan	Rehman *et al.* (2014*a*)

improved the storage potential of low-vigour seeds (Pandita and Nagarajan 2000). The improved longevity of low-vigour seeds is due to increased initial seed viability and reduced rates of seed deterioration. The major cause of seed deterioration is damage to subcellular components and cellular membranes by harmful free radicals generated by peroxidation of polyunsaturated and unsaturated membrane fatty acids. Free radical scavenging enzymes and antioxidants convert the free radicals into less harmful products, such as hydrogen peroxide and water (Powell *et al*. 2000).

Priming strategies involve rapid redrying after hydration; therefore, alternative redrying procedures, rehydration and dehydration may be beneficial for extending the longevity and retaining the benefits of primed seeds (Butler *et al*. 2009). Bruggink *et al*. (1999) reported that reducing seed moisture to avoid desiccation in mild water and temperature stress treatments extended the longevity of primed seeds.

Prolonged storage can reduce germination and seedling growth of primed seeds, particularly when stored at 25°C versus 4°C, due to restricted starch metabolism. Sometimes repriming or thermal treatments after storage cannot restore the viability of primed seed (Hussain *et al*. 2015). In most cases, priming benefits start to disappear 15 days after storage, and post-priming strategies such as temperature may affect longevity.

Recently, Wang *et al*. (2018) showed that relative humidity (RH) is the main culprit in reducing the longevity of primed seeds, not oxygen or storage temperature. These authors reported that low RH or temperature during the storage of primed rice seeds extended their longevity. Deterioration and reduced viability of primed seeds at high RH were associated with restricted starch metabolism and a decrease in antioxidant activities during storage (Wang *et al*. 2018).

Priming, in general, reduces the longevity of high-vigour seeds but improves the longevity of low-vigour seeds (Pandita and Nagarajan 2000). After priming, high-vigour seeds have almost reached Stage III (a more advanced physiological stage) and are thus more prone to deterioration. Low-vigour seeds, when primed, require more time to repair the metabolic lesions incurred before any advance in germination can occur, thus preventing further deterioration (Pandita *et al*. 2010). This necessitates developing a method to restore the longevity of high-vigour seeds after priming and retain viability during storage (Kranner *et al*. 2010).

The possible mechanisms of deterioration of primed cereal seeds during storage include restricted starch metabolism and high lipid peroxidation in oil-rich seeds at high temperature (25°C). The high viscosity of protoplasm reduced molecular mobility in the cytoplasm, limiting the deteriorative process at low seed moisture content (Gurusinghe and Bradford 2001). Among the starch molecules, oligosaccharides have a protective role that contributes to extended storage (Obendorf 1997) because they are degraded into simple sugars, such as glucose, fructose and sucrose, during germination and priming (Gurusinghe and Bradford 2001). However, the relationship between altered sugar ratio and longevity during the storage of primed seeds is inconsistent (Gurusinghe and Bradford 2001). The correlation between changes in HSPs or immunoglobulin binding protein (BiP) and seed longevity after priming may contribute to the extended storage of primed seed.

A post-priming treatment with a moderate reduction in seed water content followed by incubation for 2–4 h at 40°C or 37°C restored potential longevity in tomato (*Lycopersicon esculentum* L.) seeds (Gurusinghe *et al*. 2002) by increasing levels of BiP, an endoplasmic reticulum-resident homologue of cytoplasmic HSP70 responsible for restoring the function of proteins damaged by stress and acting as a chaperone for the reactivation of proteins damaged during the imbibition and drying steps of seed priming. However, certain storage proteins are detected only during seed priming, not during germination, such as the degradation products of certain storage proteins (cruciferin, globulins).

Priming makes DNA more susceptible to damage during storage due to changes in proteins involved in the maintenance of the structure and integrity of DNA during hydration. Because priming affects the early stages of germination (possibly due to the early initiation of metabolic processes, DNA and protein repair) cellular components such as DNA, membranes and proteins are more vulnerable to rapid deterioration during storage (Gallardo *et al*. 2001). Sano *et al*. (2017) showed that the expression of genes associated with brassinosteroid biosynthesis signalling and cell wall modification are related to seed longevity in *A. thaliana* L. Priming with small molecule cell cycle inhibitors such as aphidicolin, hydroxyurea and oryzalin may retain seed storability by limiting the cell cycle progression step during priming (Sano and Seo 2019).

To maximise the benefits of priming, emphasis should be given to the seed drying process for safe storage and the packaging material to maintain dryness and viability after redrying. Because most farmers cannot afford or have access to cold storage facilities, the ‘dry chain’ concept can be a win–win approach and pragmatic solution. The theory behind this concept is to maintain seed dryness after redrying by lowering its moisture content throughout the supply chain (Bradford *et al*. 2018). Recently, Bakhtavar *et al*. (2019) observed high germination percentage and starch and crude protein content after 4 months storage with an initial seed moisture content of 8% and 10% in Super bags (GrainPro Inc., Concord, MA, USA). Other options for extending the longevity of primed seeds during storage need to be addressed, and further research is needed to evaluate the storability of other physical and biological priming treatments that do not involve soaking and redrying.

Integration of seed priming with other physiological and molecular strategies

Seed priming is an effective and viable option for enhancing crop productivity. Additional benefits, such as improved crop yields, nutritional quality and abiotic stress endurance, may be possible if integrated with a foliar application as a complementary approach. Some reports of such integration are available, including the use of micronutrients (Zn; Mohsin *et al*. 2014), plant extracts (moringa, sorghum; Imran *et al*. 2013; Rehman *et al*. 2017) and signalling molecules (e.g. H_2O_2) with bioregulators (ascorbate, glutathione, paclobutrazol; Waqas *et al*. 2017), in various crops to enhance seedling performance, yield and nutritional quality under stress conditions. As a complementary approach, seed priming can be integrated with genetics, as evidenced by enhanced submergence and low P tolerance in varieties containing QTL of *Sub1* such as Swarna and *Pup1* in IR74 (Ella *et al*. 2011; Sarkar 2012; Pame *et al*. 2015). However, information regarding cost-effectiveness, field application and environmental replication is required before recommendations can be made.

Seed priming induces resistance to salt and drought from stress-invoked memory in the harvested progeny of wheat and chickpea that have experienced terminal drought or heat (Tabassum *et al*. 2017). Such integration of stress-invoked memory in primed seeds with molecular approaches may contribute significantly to enhanced seed vigour that can be delivered to the next generation of seeds to develop crop resilience.

Conclusions

Seed priming, through the induction of a series of biochemical, physiological, molecular and subcellular changes, is beneficial for improving seed germination, seedling vigour, uniform stand establishment, physiological phenomena and grain yield in various crops. Being a cost-effective methodology, it is a practical approach to reducing the gap between potential and actual yields, even under stressful conditions. Moreover, seed priming has considerable potential to enhance tolerance in field crops to abiotic and abiotic stresses by improving the photosynthetic rate, triggering the antioxidant system to strengthen plant defence mechanisms and stabilising membrane integrity. Micronutrient deficiency, particularly Zn, B and Fe, is increasingly affecting the human population worldwide. Priming seeds with different micronutrients, by acting upon metal-dependent enzymes and proteins, will significantly improve sugar metabolism, final harvest and grain micronutrient contents in various crops to help reduce malnutrition, particularly in developing countries. Seed priming enables farmers to optimise yields using fewer resources, and is ultimately an effective approach for farmers and those self-sufficient in food production to improve their socioeconomic conditions and achieve food security globally.

Conflicts of interest

The authors declare no conflicts of interest.

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Chapter **17**

Sustainable Agriculture

Agriculture has been the basic source of subsistence for man over thousands of years. It provides a livelihood to half of the world's population even today. According to the Food and Agricultural Organisation (FAO), people in the developing world where the population increase is very rapid, may face hunger if the global food production does not rise by 50–60 per cent. The contribution of developing countries to world agricultural production in 1975 was about 38 per cent, while that of developed countries, which account for 33 per cent of world's population, was 62 per cent. Only those countries, which can match the demands of the increasing population with increased production, can escape mass hunger. In the pre-independence period, Indian agriculture was usually described as a gamble with monsoons. There used to be a great deal of uncertainty about crop prospects, as monsoons played a decisive role in determining agricultural output and their failures resulted in widespread famine and misery. In the last few years, Indian agriculture has made impressive progress and so is more resilient to the vagaries of the monsoon, although the country's population increased from 361 million in 1951 to more than one billion in 2005.

During this period, the size of farm holdings and the per capita availability of agricultural land have also been decreasing and they are expected to be around 1.4 and 0.14 hectares respectively, by the turn of this century (Table 17.1). With competing demands on land for other sectors of development, this decline is likely to aggravate further.

Table 17.1. Statistics on Population, Food Production and Land Resources

Particulars (*1*)	*1981* (*2*)	*2000 A.D.* (*3*)	*2050 A.D.** (*4*)
1. World population (Billion)	5	6.1	9
2. India's population (Billion)–Total	0.7	1.0	1.4
(*a*) Rural	0.627 (1991)	0.750	0.500
(*b*) Urban	0.217 (1991)	0.250	0.900
3. Per capita availability of land (in ha)	0.94 (1950)	0.15 ha	...

(Contd.)

Particulars (*1*)	*1981* (*2*)	*2000 A.D.* (*3*)	*2050 A.D.** (*4*)
4. Food production (million tons)	175 (1950)	206	550
5. Per capita availability of food grains (g/day)	395 (1950)	573 (1991)	589 (2000)
6. Degraded lands (million ha)	145 (1968)	175 (1990)	Due to deforestation alone 1.3 m.ha. of forest area lost every year

* Projections.

World population today is about more than 6 billion. It is projected to become over 8 billion by 2025 and nearly 10.5 billion by the end of next century. In simple terms, the basic food production must double to maintain the status quo. The hunger must be banished from the surface of earth, as a first responsibility of any civilised society to provide sufficient food for the people who are below the poverty line.

17.1 INDIAN AGRICULTURE BEFORE THE GREEN REVOLUTION

Our traditional farming systems were characterised mainly by small and marginal farmers producing food and basic animal products for their families and local village communities. Farming was highly decentralised with individual farmers deciding on the types of crops to grow depending on climate and soil conditions. These traditions consisted of methods for controlling pests and diseases, and for building soil fertility and structure in their own ingenious ways, since farming did not include the use of chemical pesticides or fertilizers. Rather, soil health and pest control were achieved using practises such as shifting cultivation, conservation, the use of animal manures and farm wastes and the introduction of legumes into crop rotations. By growing a mixture of crops in the fields, early farmers insulted themselves from total crop failure caused by weather or pest epidemics. Even, Alexander Walker, resident at Baroda in Gujarat, wrote in 1820 that green fodder was being grown throughout the year; intercropping, crop rotation, fallowing, composting and manuring were practised; all these allowed continued farming on the same land for more than 2000 years without drop in yields. Further, the crops were relatively free from pests. One of the reasons for the decline in their sustainable system of agriculture was the land revenue collected by the British. A tax of 50 per cent and sometimes as much as 63 per cent revenue was collected and hence more than a third of the irrigated land went out of production. Similarly, an environmentally stable form of tree and forest conservation, which had been developed over the ages, crumbled. Even sacred groves, which were preserved since time immemorial, were turned into coffee, tea, teak wood and sugarcane plantations. Hence, from 1865 through 1900 India experienced the most severe series of protracted famines in its entire history.

17.2 THE GREEN REVOLUTION

After the green revolution was launched in India, substantial increase in the production of food grains was achieved through the use of improved crop varieties and higher levels of inputs of fertilizers and plant protection chemicals. But it has now been realised that the increase in production was achieved at the cost of soil health and that sustainable production at higher levels is possible only by the proper use of factors, which will help to maintain the fertility of the soil. In fact, about 60 per cent of our agricultural land currently under cultivation suffers from indiscriminate use of irrigation water and chemical fertilizers. The gravity of environmental degradation resulting from faulty agricultural practices has caused alarm among the concerned farmers, scientists and conservationalists and greater viable and sustainable farming systems have become a necessity. There has been a series of scientists and policy conference on this issue. One such alternative agriculture system which will help to overcome the problems of soil degradation and declining soil fertility is organic farming and ecological agriculture.

Most of the growth in the food production during the green revolution period is attributed to the higher fertilizer use. The growth of the fertilizer industry in India between 1965 and 1983 has been remarkable. The per hectare consumption of NPK increases from 0.6 kg in 1950 – 50 kg by 1987–88. However, the available data show that the fertilizer consumption is largely confined to irrigated areas which constitute only about 30 per cent of the gross cropped area. The annual fertilizer consumption is expected to rise to about 20 million tonnes by the turn of this century. This rise in fertilizer use is anticipated because:

- N deficiency will continue to be universal in Indian soils.
- Deficiency of P will be next in the order.
- K will become limiting in high productive regions.
- In at least half of the Indian soils, crops would benefit from Zn treatment.
- S deficiency will limit the productivity in a vast majority of Indian soils.

17.2.1 Impact of Green Revolution on the Environment

To increase the agricultural production in the country and to meet the requirements of the expanding population, it became imperative to change the methodologies of crop production. These involved the use of high-yielding varieties and higher fertilizer dosages; increasing the irrigated area and intensive cropping; bringing large areas under one crop; growing crops in non-conventional areas; and changing the crop sequences. The green revolution followed the development of commercial agriculture in the developed countries after World War II, Chemical companies that developed highly toxic and life damaging chemicals for the purpose of warfare, decided to turn their attention on the chemical control of insects, pests and unwanted plants in the farmer's fields. In addition, the production of petroleum-based fertilizers by oil companies was used to replace composts and manures. The food grain production increased dramatically as the policies of green revolution began to take effect. By the year 2000, India will need to produce 230 million tons of food grains on 140 million hectares of agricultural land in order to feed an estimated 1 billion Indians.

This achievement, though remarkable, has also coasted us dearly. Along with the increase of food grain production pesticide consumption in India also increased considerably. In 1932 nearly 200 metric tons of chemical pesticides were used, but by 1975 it was 25,000 metric tons, an astounding 375 fold increase over 30 years. Despite increasing use of pesticides, annual crop losses due to pests still amount to more than 15,000 crores. Consumption of chemical fertilizers has gone up seven times in the last 20 years, but production has only increased a miserable two-fold. While we now have enough food ourselves and are concentrating on broadening our food exports, we have apparently sadly overlooked on equitable food distribution to our hungry millions. It is quite unfair to balance our country's trade deficit, caused by expanding imports of petroleum-based products with food exports at the expense of making the same available for local consumption. The modern agriculture techniques such as use of synthetic fertilisers and pesticides are continuing to destroy stable traditional ecosystems and the use of high yielding varieties of crop has resulted in the elimination of thousands of traditional varieties, with the concurrent loss of genetic resources. In the past, our fore-fathers were consuming chemical-free foods, but now a large quantity of chemical residues getting into the food chain and toxic residues in agricultural commodities is an issue of major concern to everybody.

Our major concern is to meet the internal demands of farm production without degrading the productive environment. Sustainability issues have become highly relevant even under the low input use situations. There is hardly any scope of finding new land area suitable for cultivation. Since the ability of the land to produce food is limited and the limits of production are set by soil and climatic conditions, there are critical levels of population that can be supported in perpetuity from any given land area. Any attempt to produce food in excess for the restrictions set by soil and climatic conditions will, in the long term, result in failure. Degradation of land, hunger and eventual reduction in population are the outcome of such practises. However, the application of technological innovations in the form of new seeds, fertilizers, irrigation and suitable management strategies has bailed such catastrophic predictions in the past. This underscores the tremendous potential of science and shows the possibility of meeting the demands put on our farm production systems without reducing its sustainability, through scientific research.

The progress in Indian agriculture during the last 40 years can be broadly classified under three areas: First, progress in developing the research and educational infrastructure, essential for generating and testing technologies suitable for different agro-ecological regions, secondly, a reasonably efficient input production and delivery system for the production and distribution of seeds, fertilisers and other inputs. Thirdly, evolving policies essential for stimulating higher production by small farmers and increased consumption by the rural and urban poor. Thanks to these steps, growth of food production has on the whole remained above the rate of population growth. Statistics on agricultural production in India from 1960–1988 show that during the period (*a*) the gross cropped area increased marginally; (*b*) the area under irrigation nearly doubled; (*c*) the high yielding variety programme, initiated at the national level in 1966, increased to cover nearly 39 per cent of the cropped area; (*d*) the total food production increased from 74 million tonnes to nearly 174 millions tonnes; and (*e*) both the fertiliser and pesticide consumption increased more than 25 times. The ratio of pesticide to fertilizer remained nearly constant at 1:100. Interestingly, the use of pesticides in the public health sector, which has higher than in the agricultural sector until 1966, became almost equal in 1970 and declined significantly thereafter. The number of pesticides used in agricultural sector has always been a more diversified than in public health sector which used only DDT, HCH and malathion.

The introduction of high-yielding varieties changed the agricultural environment leading to numerous pest problems of economic importance. Many of these were either unknown or were minor importance in the early 1960's. Increased irrigation, higher usage of fertilizers and wide adoption of high-yielding varieties led to the resurgence of pests. The high-yielding varieties and the monoculture practices led to material changes in the pest complex. Pests and diseases such as gall midge, brown plant hopper, bacterial blight and tungro virus of rice, which were of minor importance before the green revolution, suddenly assumed major proportions; for instance, S*podoptera litura* on cotton, maize and tobacco; Pyrilla on wheat, maize and sorghum; apple scab and codling moth on apple and Karnal bunt on wheat increased the crop losses due to pests enormously. An important aspect of the resurgence of newer pests in the time-lag between the introduction on of a new variety/agronomic practice and the actual manifestation of the pest epidemic. This varies with pest and the crop. For example, in the rice bacterial wilt there was a practically no time-lag in the very first season of the introduction of Taichung Native-

1 in Andhra Pradesh in 1963, the disease broke out. In the case of the rice tungro virus, it took four to five years before the disease manifested itself in a virulent form. It took, however, a decade for the brown plant hopper to become a major pest. Similarly, every variety of hybrid bajra, when released, was thought to be tolerant/resistant to downy mildew, but within a few years all proved to be susceptible. Since the high-yielding varieties were more prone to pests and diseases, use of pesticides increased and this brought about (*a*) widespread occurrence of pesticide residues in nearly every agricultural commodity; (*b*) increased pesticide resistance in vectors; (*c*) resistance to pesticides in stored grain pests which was first reported in 1971 and by 1979 six major pests of stored grain became resistant to a number of insecticides and fumigants; and (*d*) pesticide resistance in pests of agricultural importance becoming an important constraint in increasing productivity. This is true especially for the polyphagous pests such as *Spodoptera litura* (tobacco caterpillar); *Plutella xylostella* (diamond back moth) and *Heliothis armigera* (American boll worm). It is suspected that the *Aphis craccivora* (black aphid), a serious pest of pulses, and *Lipahis erysimi* (Mustard aphid) have also developed resistance to pesticides.

The ills of green revolution are stated to be:

- reduction in natural fertility of the soil
- destruction of soil structure, aeration and water holding capacity
- susceptibility to soil erosion by water and wind
- diminishing returns on inputs (the ratio of energy input to output halves every 10 years)
- indiscriminate killing of useful insects, micro organisms and predators that naturally check excess crop damage by insect pests
- breeding more virulent and resistant species of insects
- reducing genetic diversity of plant species
- pollution with toxic chemicals from the agrochemicals and their production units
- endangering the health of the farmers using chemicals and the workers who produce them
- poisoning the food with highly toxic pesticide residues
- cash crops displacing nutritious food crops
- chemicals changing the natural taste of food
- high inputs increasing the agricultural expenses
- Increasing the farmer's work burden and tension
- depleting the fossil fuel resources
- increasing the irrigation needs of the land
- big irrigation projects often resulting in soil salinity and poor drainage
- depleting the ground water reserves
- lowering the drought tolerance of crops
- appearance of 'difficult' and problematic weeds
- heightening the socio-economic disparities and land holding concentration
- high input subsidies leading to inflationary spirals
- increasing the political and bureaucratic corruption
- destroying the local culture (commercialisation and consumerization displacing self-reliance)
- throwing financial institutions into disarray (as impoverished farmers demand write-off of loans)
- agricultural and economic problems sparking off social and political turmoil resulting in violence.

17.3 SUSTAINABLE AGRICULTURE

Earlier, the subsistence level of farmers forced to over exploit natural resources by way of mining soil nutrients, cultivating in steep slopes, overgrazing rangelands and excessive collection of fuel wood in order to survive. Now modern crop production technology has considerably raised the yield but has created problem of land degradation, chemical residues in farm produce and atmosphere and water pollution. Hence modern agriculture was not sustainable.

Sustainable agriculture is the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of environment and conserving natural resources. **Sustainable agriculture** is also known as ecofarming (as ecological balance is important) or organic farming (as organic matter is the main source of nutrient management) or sometimes as natural farming or permaculture. Some other designated it as regenerative agriculture or alternative farming. Sustainable agriculture is a food and fiber production and distribution system that:

- Supports profitable production;
- Protects environmental quality;
- Uses natural resources efficiently;
- Provides consumers with affordable, high-quality products;
- Decreases dependency on nonrenewable resources;
- Enhances the quality of life for farmers and rural communities, and
- Will last for generations to come.

17.3.1 Role

Small landholders in the tropics are mainly fed up with rain fed farming and it is being carried out with high risk. In a constant struggle to survive, farm communities have developed numerous ways of obtaining food and fiber from plants and animals (TAC/CGAIR, 1988). A wide range of different farming systems have been developed, each adapted to the local ecological conditions (Okigbo, 1978) Richards, 1988: Dupre, 1990). A closer look at these traditional farming systems reveals that they are not static; they have changed over the generations–and particularly quickly over the last few decades–primarily as a result of the research and development activities of the local people. (Wieskel, 1989; Owasu, 1990). However, rapid changes in economic, technological and demographic conditions demand adjustments in smallholder farming systems. New market opportunities, promotion of chemical inputs and financial constraints may lead farmers to seek short term profits and pay less attention to keeping their agriculture in balance with the ecological conditions. In recent years, the negative environmental and soil impacts of High External Input Agriculture (HEIA) have become increasingly obvious (Wali, 1992; NRC, 1993). At the same time, many disadvantaged communities of smallholders are being forced to exploit the resources available to them so intensively that, environmental degradation is setting in. Hence, it is important to seek new approaches to agricultural development, which will benefit small farmers, half degradation of natural resources and restore degraded soils and ecosystems.

In 1987, the World Commission on Environment and Development (WCED, 1987) called attention to the immense problems and challenges facing world agriculture for meeting present and future food needs, and to the need for a new approach to agricultural development. The agricultural systems that have been developed over the past few decades have contributed greatly to the alleviation of hunger and the raising of standard of living of poor people (Dora, 1983; Wilken, 1987) who have served their purposes up to a point. But they were developed for the purposes of a smaller, more fragmented world. However, new realities reveal their inherent contradictions, realities while require agricultural systems that focus as much attention on people as they do on technology, as much on resources as on production, as much on the long term as on the short term. Only such systems can meet the challenges of the future (WCED, 1987).

17.3.2 Concepts and Basic Principles

A. Concept

The use of modern farming practices has greatly enhanced the productivity of crops. However, the hazards of the use of agricultural chemicals in causing eco-degradation have prompted many to think rationally and evolve alternatives. The negative impact of pesticides on the environment has been well documented. Pesticides are not specific to the target organisms and kill many useful organisms, thus upsetting the food web in nature. Further, some resistant pests survive even after pesticide application; therefore, higher doses are required to kill them. The pesticide residues in the food chain have endangered the life sustaining systems. Finally, lack of safety measures in the use of pesticides pose adverse health effects on people. The synthetic fertilizers have also jeopardized the environment through nitrate poisoning and exterminating the beneficial soil microflora and microfauna by adversely altering the chemical and physical properties of the soil. Though the agricultural extension personnel are aware of the ill effects of modern technology, they are helpless without an effective alternative system. Therefore, the need for sustainable and ecological agriculture is increasingly felt in the world.

Sustainable agriculture is also referred by other names such as alternative agriculture, ecological agriculture and natural organic farming. It is that form of farming which maintains or enhances the flow of its products without damaging its own long term potential. The United States National Research Council (1989) defined alternative agriculture as "those alternative systems incorporating natural processes reducing the use of inputs of off-farm sources, ensuring the long term sustainability of current production levels and conserving soil, water, energy and biological resource: Organic farming is an agricultural production system, which avoids or largely excludes the use of systematically compounded fertilizers and pesticides. To the maximum extent feasible, organic farming systems rely upon crop rotations, crop residues, animal manures, legumes, green manures to maintain soil productivity and tilth to supply plant nutrients. It looks forward to alternative methods of pest-control like pest resistant cultivars, bio-control agents and cultural methods of pest-control. Such ecological farming systems are highly productive and they should not be mistaken for a reversion to inefficient and less productive farming methods. The adoption of ecological farming is not as simple as one may presume. It is highly knowledge intensive, labour-oriented and a complex system integrating several organic recycling processes.

B. Basic principles

Principle: The use of limited quantities of fertilizers and discrete application of small quantities of target specific pesticides at critical stages of crop damage thereby overcoming the effects of modern agriculture.

The following seven principles will have to be kept in view to achieve success in promoting ecological agriculture:

- Based on both biological potential and biological diversity, land can be classified into conservation, restoration and sustainable intensification areas. Conservation areas are rich in biological diversity and must be protected in their pristine purity. Soils with diminished biological potential are also referred as waste or degraded lands and it should be improved through the adoption of principles of restoration ecology. The diversion of land suitable for sustainable farming should be prevented by legislation. Such lands should be subjected to a continuous soil health monitoring.
- Effectiveness in water saving, equity in water sharing and efficiency in water delivery and use are important for sustainable management of available surface and groundwater resources. There

should be an integrated policy for conjunctive and appropriate use of river, rain, ground, sea and sewage water.

- An integrated system of energy management involving the use of renewable and non-renewable resources of energy in an appropriate manner is essential for achieving desired yield levels.
- Soils in India are often not only thirsty but also hungry. There is a need for reduction in the use of market purchased inputs and not of inputs *per se*. It is in this context integrated systems of nutrient supply assume importance. The components of the integrated nutrient supply system suitable for easy adoption include crop rotation, green manures and biofertilizers. Biodynamic systems that make significant use of compost and humus will help improve soil structure and fertility.
- Genetic diversity and location specific varieties are essential for achieving sustainable advances in productivity. Genetic homogeneity characteristic of modern agricultural systems only leads to greater genetic vulnerability to biotic and abiotic stresses. Diversity of crops and crop varieties will help enhance the yield stability.
- The control of weeds, insect pests and pathogens is one of the most challenging jobs in agriculture. Therefore, an integrated pest management system needs adoption. The conservation and wise use of genetic diversity is essential for breeding strains possessing multiple resistances to biotic and abiotic stresses. Similarly, the conservation of natural enemies of pests is important for minimizing the use of chemical pesticides and for avoiding the multiplication of insecticide resistant pests. Botanical pesticides such as those derived from neem, need popularization. Selective microbial pesticides offer particular promise, of which, strains of *Bacillus thuringiensis* (Bt) serve as an example. Transgenic techniques have made the transfer and expression of Bt toxin possible in several crops.
- Whole plant utilization methods and preparation of value added products from the available agricultural biomass are important both for enhancing income and for ensuring good nutritional and consumer acceptance properties. Both producers and consumers will not derive benefit from production advances if there is a mismatch between production and post-harvest technologies.

C. Feasibility

The shift from chemical to ecological agriculture should be gradual. A sudden switch over could spell disaster and discourage farmers from taking to this course. At least seven to eight years will be needed for the transition and during the interim years the farmers could build up a sufficient organic base to fertilize the fields and improve the fertility of soil. From a purely ecological point of view, ecological farms should have more diversity of species of plants, which invite different species of birds and beneficial insects. As ecological equilibrium is established, the build up of specific pests and pathogens is significantly reduced.

The biggest problem faced by most ecological farmers is that they do not know how to start switching the transition phase, which poses a great challenge, and they do not have any information on how to shift. There is no organized extension machinery to disseminate the proven technologies and in many cases the basis information itself is not available. When the farmers proceed to change the soil fertility using organic manures, they often ignore other aspects of the farming system. For instance, they forget the plant protection aspect. There are no immediate alternatives available to chemical control in the market. One has to develop effective alternatives. So far they are only left with the adoption of preventive methods. Simple changes in transition lead to complications in pest and disease management. Plant derived products are there but they are not as effective as synthetically compounded ones and therefore cannot be an efficient substitute. Farmers should get trained in pest monitoring. While calculating nutrient balances, ecological farmers should show least dependency on purchased inputs and in addition they must use these little inputs quite efficiently. There have been several positive steps towards this direction. Integrated pest management and nutrient recycling systems have been advocated widely. The heavy reliance on synthetic agro-inputs is gradually removed by substituting farm-grown inputs both for ecological and economic reasons. With more agricultural research institutes, and progressive farmers focusing greater attention on the sustainable agricultural practices, it is opined that more useful practical methods will emerge to profit small and marginal farmers.

D. Goals

Sustainable agricultural systems must maintain or enhance biological and economic productivity of crops, (*ii*) enhance the efficiency of use of input, (*iii*) lesser adverse environmental impacts both on and off the farm, (*iv*) minimize adverse environmental impacts on adjacent and down stream environments, (*v*) minimize the magnitude and rate of soil degradation and to enhance soil quality and resilience so that the crop productivity can be sustained with minimum adverse impact on soils and environment, and (*vi*) enhance compatibility with social and political conditions.

The word 'sustainability' is now widely used in development circles. But what does it really mean? According to a dictionary definition, 'sustainability' refers to 'keeping an effort going continuously, the ability to last out and keep from falling'. In the context of agriculture, 'sustainability' basically refers to the capacity to remain productive while maintaining the resource base. For example, the Technical Advisory Committee of the Consultative Group on International Agricultural Research (TAC/CGIAR 1988) states: "sustainable agriculture is the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources".

However, many people use a wider definition, judging agriculture to be sustainable if it is (after Gips 1986);

- ***Ecologically sound***, which means that the quality of natural resources is maintained and the vitality of the entire agro-ecosystem from humans, crop and animals to soil organisms–is enhanced. This is best ensured when the soil is managed and the health of crops, animals and people is maintained through biological processes (self-regulation). Local resources are used in a way that minimizes losses of nutrients, biomass and energy, and avoids pollution. Emphasis is on the use of renewable resources.
- ***Economically viable***, which means that farmers can produce enough for self-sufficiency and/or income, and gain sufficient returns to warrant the labour and costs involved. Economic viability is measured not only in terms of direct farm produce (yield) but also in terms of functions such as conserving resources and minimizes risks.
- ***Socially just,*** which means that resources and power are distributed in such a way that the basic needs of all members of society are met and their rights to land use, adequate capital, technical assistance and market opportunities are assured. All people have the opportunity to participate in decision-making, in the field and in the society. Social unrest can threaten the entire social system, including agriculture.
- ***Humane,*** which means that all forms of life (plant, animal, human) are respected. The fundamental dignity of all human being is recognized, and institutions incorporate such basic human values as trust, honesty, self-respect, cooperation and compassion. The cultural and spiritual integrity of the society is preserved and nurtured.

- ***Adaptable,*** which means that rural communities are capable of adjusting to the constantly changing conditions for farming, population growth, policies, market demand etc. This involves not only the development of new appropriate technologies but also innovations in social and cultural terms.

These different criteria of sustainability may conflict and can be seen from different view points; those of the farmers, the community, the nation and the world. There may be conflicts between present and future needs; between satisfying immediate needs and conserving the resource base. The farmer may seek high income through high prices for farm products; the national government may give priority to sufficient food at prices, which the urban population can afford. Choices must continually be made in a never-ending search for balance between the conflicting interests. Therefore, well-functioning institutions and well deliberated polices are needed on all levels-from village to global in order to ensure sustainable development.

In agricultural development, raising production is often given primary attention. But there is an upper limit to the productivity of ecosystems. If this is exceeded, an ecosystem will degrade and may eventually collapse, and fewer people will be able to survive on the remaining resources than before. This implies that, when the limits on the supply side are reached, something has to be done on the demand side, *e.g.* other sources of income, emigration, lower consumption level, and population control. Production and consumption have to be brought into balance on an ecologically sustainable level. Although sustainability must be seen as a dynamic concept, which allows for the changing needs of an increasing global population (TAC/CGIAR, 1988), basic ecological principles oblige us to recognize that agricultural productivity has finite limits.

Why has the concept of sustainability gained increasing importance with reference to agricultural development? This becomes evident if we take a look at the present situation of world agriculture. The Goal of sustainable agriculture is to feed the expanding population while farming in an economically sound and regenerative way. Economically viable system that minimizes the purchase of off farm inputs such as pesticides and fertilizers and rely on on-farm renewable resources, form the important factor in sustainable agriculture. It emphasizes soil building practices through crop residues, animal manures, green manures, etc., Nature pest control and crop rotations with N fixing legumes ensure substitution of external resources by internal resources, reduce production costs and are ecologically sound. Modern agricultural systems are capital intensive. Economic returns require use of high level of inputs. Injudicious use of input leads to environmental pollution. Such system does not endure long. A farming system to be sustainable should have the capacity to endure indefinitely. Therefore the ultimate goal of sustainable agriculture is "*to develop farming system that are:* (*a*) *productive,* (*b*) *profitable,* (*c*) *conserve the natural resource base,* (*d*) *protect the environment, and* (*e*) *enhance soil health and safety over a long term'*. Hence, this can be referred as *Eco-friendly Agriculture.*

17.3.3 Sustainability through Farming Systems

Two farming systems have been proposed for enduring sustainability. They are:

17.3.3.1 Low external input sustainable Agriculture or Low input sustainable Agriculture (*LEISA/LISA*)

It means Minimal use of external production inputs. In view of the limited access of most farmers to artificial external inputs, the limited value of these inputs under LEIA conditions, the ecological and social threats of 'green revolution' technology and the dangers of production on nonrenewable energy sources, the strong emphasis on High External Input Agriculture (HEIA) in agricultural development must be questioned. However, it is also open to question whether it will be possible to raise world food production sufficiently without the use of such external inputs. Besides, natural as opposed to artificial inputs can also have detrimental environmental effects.

LEISA is an option which is feasible for a large number of farmers and which can complement other forms of agricultural production. As most farmers are not in a position to use artificial inputs or can use them only in small quantities, it is necessary to concentrate on technologies that make efficient use of local resources. Also, those farmers who now practice HEIA could reduce contamination and costs and increase the efficiency of the external inputs by applying some LEISA techniques. It is important that the agro-ecological knowledge of both scientists and farmers can be applied, so that internal and external inputs can be combined in such a way that the natural resources are conserved and enhanced. Productivity and security are increased and negative environmental effects are avoided.

A. LEISA refers to those forms of agriculture that

- Seek to optimize the use of locally available resources by combining the different components of the farm system, *i.e.,* plants, animals, soil, water, climate and people, so that they complement each other and have the greatest possible synergetic effects.
- Seek ways of using external inputs only to the extent that they are needed to provide elements that are deficient in the ecosystem and to enhance available biological, physical and human resources. In using external inputs, attention is given mainly to maximum recycling and minimum detrimental impact on the environment.
- LEISA does not aim at maximum production of short duration but rather at a stable and adequate production level over the long term. LEISA seeks to maintain and, where possible, enhance the natural resources and make maximum use of natural processes. Where part of the production is marketed, opportunities are sought to regain the nutrients brought to the market.

Numerous developing countries are now implementing so-called structural adjustment programs that involve policies such as devaluation of exchange rates, reduction of government spending and intervention, reduction of subsidies and removal of price controls. In this way, the demand for imports is to be curtailed and the purchase of local goods stimulated, so as to reduce the balance of payment and government deficits and to promote national economic growth. LEISA appears to fit within this context, as it is less demanding on imports and credits than the conventional approach to agricultural development. At farm, regional and national level, LEISA implies the need for closely monitoring and carefully managing flows of nutrients, water and energy in order to achieve a balance at a high level of production. Management principles include harvesting water and nutrients from the watershed, recycling nutrients within the farm, managing nutrient flow from farm to consumers and back again, using aquifer water judiciously, and using renewable sources of energy. As these flows are not confined by farm boundaries, LEISA requires management not only at farm level but also at district, regional, national and even international levels. At each level, technologies are sought to make the flow cycle as short as possible and to balance the flows. In this book, the focus is on practices that can be applied at farm level. Questions related to techniques and system at village level and above are equally important, but should be addressed in a separate study.

LEISA incorporates the best components of indigenous farmers' knowledge and practices; ecologically sound agriculture developed elsewhere, conventional science and new approaches in science (*e.g.,* systems approach, agro-ecology, biotechnology). Thus, conventional science has served mainly HEIA, but the contributions could make to LEIA should be explored to the full. LEISA practices must be developed within each ecological and socioeconomic system. The specific strategies and techniques will vary accordingly and will be innumerable. The experience thus far of developing LEISA systems cannot provide universal, ready-made answers for the problems of farmers in other areas, but can provide some indications of principles and promising possibilities.

The process of combining local farmers' knowledge and skills with those of external agents to develop site-specific and socio economically adapted farming techniques has been given the name 'participatory Technology Development' (PTD). Farmers work together with professionals from outside their community (*e.g.,* extension workers, researchers etc.) in identifying, generating, testing and applying new techniques. PTD seeks to strengthen the existing experimental capacity of farmers, and to encourage continuation of the innovation process under local control (Haverkort, *et al.,* 1988). The experience of combining indigenous and scientific knowledge through a process of PTD indicates strongly that it is indeed possible to transform LEIA to LEISA (Low External-Input and Sustainable Agriculture). This approach to agricultural development appears to be better adapted to the needs and opportunities of LEIA farmers and to fit better into their cultural context than the conventional approach.

B. Sustainable agroecosystems

An alternative to the chemical dependence is to maximize the contributions of bio diversity to pest control and nutrient cycling and to attain optimal productivity with minimal inputs. Edwards and Grove (1991) proposed an analogous term for management of nutrients, integrated nutrient management. This approach capitalizes the adaptive features of traditional systems and incorporates additional advantages of conventional and innovative technology. It is important to recognize a strong link between the availability of organic matter and both bio diversity and nutrient cycling (Palm *et. al.,* 1987). The practice in many developing countries of removing organic matter from the land for fuel and other purposes is a serious constraint to long-term sustainability (Oram, 1988). The most sustainable farming practices and components of the man managed bio diversity can be developed only by understanding the functions of the agro ecosystem and low social and economic conditions of the farmers and their climatic and environments impact upon overall crop and animal productivity. No matter how well the agro ecosystem functions biologically, it is sustainable only if it is socially and economically sound (Altieri, 1987).

Advantages

- Production costs are low,
- Overall risk of the farmer is considerably reduced,
- Pollution of water is avoided,
- Healthy food very little or no pesticide residue is ensured,
- Ensure both short and long term profitability.

Disadvantages

Continuation of LEISA will perpetuate a vicious circle of "low input-low yields" which the third world countries with even increasing population cannot afford. The solution for this is the optimal input farming which will meet the requirement of sustainability with the promise of low input/unit of output. It lays emphasis on law of diminishing returns.

17.3.3.2 Organic Farming

A. Why organic farming?

Need for more intensive and economic agriculture production led to wide use of high doses of concentrated chemical fertilizer but insufficient use of organics led to negative results, decrease in soil fertility and soil structure. Chemical fertilisers and pesticides pollute our air and water. Agricultural chemicals, including hormones and antibiotics leave residues in food that may cause cancer or genetic damage. Other aspects of food quality have also changed for the worse. Further soil and energy resources are being depleted. Instead of recycling our wastes back into the land as fertiliser, we allow them to pollute our water. We use non-renewable energy resources to produce artificial fertiliser. In the future we may be forced to make radial adjustments in such agricultural practices. Thus organic farming requires the total elimination of the most damaging chemicals. Such restrictions would presumably satisfy most concern about pollution and human health. High-yields of crops are heavily dependent on use of chemical fertilizers. But in long run many problems are encountered.

The adverse effect of continued use of high analysis NPK can be summarized as follows:

- The occurrence of Zn and S deficiencies in many rice growing areas.
- Adverse effect on soil biotic life, particularly if the soil is acid.

B. Objectives of organic and conventional farming

It can be summarized as follows:

Organic farming	*Conventional farming*
A. Organization	
1. Ecological orientation, second economy, efficient labour input.	Economical orientation mechanization, minimising labour input.
2. Diversification, balanced combination of enterprises.	Specialisation, disproportionate development of enterprises.
3. Stability due to diversification.	Programme based on market.
B. Production	
1. Cycle of nutrients within the farm, predominantly farm produced materials.	Supplementing nutrients, predominantly bought in fertilizer.
2. Weed control by crop rotation and cultural practices.	Weed control by herbicides.
3. Pest control based on inoffensive substances.	Pest control by pesticides.
4. Housing of livestock for production and health.	Livestock rarely combined.
C. Mode of influencing life processes	
1. Production is integrated into environment, building healthy landscapes.	Emancipation of enterprises from their environment by chemical and technical manipulation.
2. Balanced conditions for plants and animals; few deficiencies need to be corrected.	Excessive fertilisation, necessitating frequent correction of nutrient deficiencies.
D. Social Values	
1. Optimum input/output ratio.	Low input/output ratio.
2. No pollution.	Considerable pollution worldwide.
3. Maximum conservation of soils, water quality and wild life.	Using up soil fertility often resulting in erosion and losses in water quality and wildlife.
4. Holistic approach.	Economic motivation.

C. Organic Vs. Natural farming

There is a misconception that organic farming is merely to say "no" to chemicalism. But apart from restricting and to the extent possible eliminating chemicals (Pesticides and fertilizers) it has something else also to convey. One who understands the whole concept of organic farming will be certainly inspired by it.

The differences between organic farming and natural farming (based on natural principles) are given below:

Natural farming	*Organic farming*
* It is not alternative system of farming but part of the philosophy of life involving continuous search to know the true spirit and form of nature.	In many respects close to natural farming, but does not have the philosophical overtone of natural farming.
* Totally eliminates all the components of modern farming.	Organic farming does not totally exclude elements of modern farming. It involves limited and essential – ploughing – hoeing, weeding, and – use of chemicals
* It indicates a 'Do-nothing' approach	It indicates a soil building programme–more intensive style of natural farming. Application of natural plant protection chemicals (which are not inorganic derivatives) use of organic manures (instead of chemical fertilisers) are permitted.
The essential principles are:	Principal elements to be considered in practising organic farming are:
* No cultivation	(*i*) maintaining a living soil.
* No chemical fertilisers	(*ii*) making available all the essential nutrients.
* No weeding	(*iii*) organic mulching.
* No plant protection.	

Nonetheless, the principles and practices that lie behind these terms are essentially similar. The objectives of organic agriculture are concisely expressed in the standard document of the International Federation of Organic Agriculture Movement (IFOAM) as follows:

- to produce food of high nutritional quality in sufficient quantity
- to work with natural systems rather than seeking to dominate them
- to encourage and enhance the biological cycles within farming system involving micro organisms, soil flora and fauna, plants and animals
- to maintain and increase the long term fertility of soils
- to use as far as possible renewable resources in locally organised agricultural systems
- to work as much as possible within a closed system with regard to organic matter and nutrient elements
- to give all livestock, conditions of life that allow them to perform all aspect of their innate behaviour
- to avoid all forms of pollution that may result from agricultural techniques

- to maintain the genetic diversity of the agricultural system and its surroundings, including the protection of plant and wildlife habitats
- to allow agricultural producers an adequate return and satisfaction from their work including a safe working environment, and
- to consider the wider social and ecological impact of the farming system.

In general, the problems ascribed to be created by the use of chemical fertilizers include high energy cost, monocropping, loss of productivity and water pollution.

1. Energy use: The increased use of fertilizers has been possible due to increase of energy input for fertiliser production. Although in developing countries about 70 per cent of the commercial energy used in agriculture goes in the production of chemical fertilisers as against 35 per cent in developed countries; total consumption is more in developed countries which account for only 37 per cent of the total agricultural area. Thus, the scope for reducing energy consumption in developing countries is marginal.

2. Monocropping: The crop yields increased greatly in developed countries over last 50 years and in developing countries during last 20 years. Most of these are due to development of varieties, which respond well to fertilisers. The different types of cropping systems practised in traditional agriculture have given way to system involving only few crops, which are highly nutrient depleting. The legumes, grasses and millets which are regular components of cropping systems in Indian agriculture have largely been phased out in highly productive areas and replaced by high yielding rice, wheat, sugarcane, etc. This has created the problems of soil erosion and disturbances to soil and wild life habitats.

3. Imbalance of nutrients and decrease in soil productivity: There is increasing concern on the role of fertilizers in maintaining long term soil productivity. In intensive agriculture with high yielding crop varieties, crop yields will be drastically reduced due to decline in the soil nutrient reserves. Long term use of only chemical (N) fertilisers also has adverse effect on soil physical properties such as bulk density, hydraulic conductivity and stability of aggregates. The deterioration in soil due to intensive cultivation can be easily arrested by the balanced use of bulky organic measure such as FYM and compost.

4. Pollution: Greater use of synthetic N and P fertilisers has given rise to concern amongst environmental and health specialists. The N fertilisers create health and ecological hazards due to presence of excess nitrate in drinking water; eutrophication of lakes and streams and depletion of stratospheric ozone due to nitrous oxide production from denitrification. The continued application of P fertilisers to agricultural lands can result in the build up of trace metal contaminants such as arsenic and cadmium contained in the fertiliser. Although the mobility of P in soil is low, transport of P from agricultural soils to aquatic environment in runoff can result in deterioration of water quality.

So to avoid the toxic effects we can go for biological agriculture which attempts to provide a balanced environment, in which the maintenance of soil fertility and control of pests and diseases are achieved by the enhancement of natural processes and cycles, with only moderate inputs of energy and resources while maintaining optimum productivity.

The rapidly growing population is also causing serious environmental problems and degrading natural resources that are essential to agriculture. Some of these problems are discussed below:

1. Soil erosion: In recent decades more and more forest and grasslands have been cleared and converted to crop fields. At the same time effective traditional soil conservation techniques have been abandoned. Thus soil erosion has become a serious and growing threat to sustained agricultural productivity. Man's increasing impact on the environment is resulted in a world-wide tendency towards degradation and erosion of soils. In Britain, 44 per cent of the arable land is subjected to erosion. It is not unusual to find fields that lose 20 t/ha/year. In worst areas the loss is as high as 50 tonnes per ha in a single year. Soil Scientists estimate that if fields repeatedly lose more than 2 t per ha, yields of cereals would fall permanently. In China the annual erosion rate is 50–70 t/ha/year and in India, it is about 16 t/ha/year. After years of intensive cultivation, the thickness of top soil has reduced from 60–70 cm to only 20–30 cm. Approximately 0.5 cm of top soil is lost annually. The seriousness of this situation becomes apparent when it is recognised that soil is formed only at approximately 1 t/ha/yr.

2. Decrease in organic matter: Severe erosion results in reduction of organic matter in the soil, the more organic matter in the soil the more stable it is. A stable soil is also more porous allowing water to drain rapidly from the surface. Water that does not penetrate the soil, runs off the surface taking soil with it. Changing in farming techniques led to depletion of organic matter in the soils. Farmers have ceased rotating grass with crops. Pasture crops maintain or even raise the amount of organic matter in the soil whereas continuous arable cropping tends to reduce these levels. Also inorganic fertilisers have largely replaced organic manures. Grass crops not only increase the amount of organic matter but also permanently cover the ground affording greater protection to erosion by rain. Organic farming techniques will help to increase the organic matter content of soils, thus reducing the bulk density and decreasing compaction. There can be effective conservation systems since they provide soil cover during most of the year and with the greater use of rotations and green manure crops, crop residues and legumes, there is an increased emphasis on manure as a source of soil fertility. So unlike under conventional and monocropping systems, due to maintenance of crop cover during greater part of the year there is a little runoff and erosion. Modern concept of conservation tillage is effective to reduce erosion but it employs excessive use of herbicides, which are hazardous to our environment.

Soil organic matter is one of the important components of the soil. The dead plant and animal remains and dead microbial tissues form the main source of soil organic matter. Various organic matter like farmyard manure, compost, green manure etc. that are added to the soil from time to time further add to the store of organic matter. These added organic undergo a series of microbial decompositions and finally humus is formed (light bulky amorphous material of dark brown to black colour). Tropical soils are generally low in organic matter content. Sandy soils contain less organic matter than loams and loams contain less than clay soils. The low organic matter is primarily due to climate particularly due to high temperature and secondarily due to cultural practices. In tropical and sub-tropical regions although much organic matter is produced, it decays very rapidly. Whatever organic matter added to the soils will be decomposed (over 90 per cent in a year) and hence, it is Herculean task to raise the organic matter content of the soil. In cultivatable soils, the organic matter content ranges from less than 1 per cent to 15 per cent. The peat soils contain more than 90 per cent organic matter.

D. Concept and Definition

The concept of organic agriculture has been perceived differently by different people. To most of them, it implies the use of organic manures and natural methods of plant protection instead of using synthetic fertilisers and pesticides. It is regarded by some as farming involving the integrated use of fertilisers and organic manures as well as of chemicals and natural inputs for plant protection. In either case the concept has been understood only partially.

Organic agriculture has been defined differently, but the description offered by Lampkin (1990) appears to be most comprehensive one covering all essential features. As per this description, organic agriculture is a production system, which avoids or largely excludes the use of synthetic compounded fertilisers, pesticides, growth regulators and livestock feed additives. To the maximum extent feasible, organic farming system rely on crop rotations, crop residues, animal manures, legumes, green manures, off-farming organic wastes and aspect of biological pest control to maintain soil productivity and tilth, to supply plant nutrients and to control insects, weeds and other pests. The concept of soil as living system that develops the activities of beneficial organisms is central to the definition.

Organic agriculture does not imply the simple replacement of synthetic fertilisers and other chemical inputs with organic inputs and biologically active formulations. Instead, it envisages a comprehensive management approach to improve the health of underlying productivity of the soil. In a healthy soil, the biotic and abiotic components covering organic matter including soil life, mineral particles, soil air and water exist in a stage of dynamic equilibrium and regulate the ecosystem processes in mutual harmony by complementing and supplementing each other. When the soil is in good health, the population of soil fauna and flora multiplies rapidly which, in turn, will sustain the bio-chemical process of dissolution and synthesis at a high rate. This state of soil life and the associated organic transformations will enhance the regenerative capacity of the soil and make it resilient to absorb the effects of climatic factors and occasional failures in agronomic management.

The success of organic agriculture depends to a great extent on the efficiency of agronomic management adopted to stimulate and augment the underlying productivity of the soil resource. In this context, the concept of agro-ecosystem becomes relevant. A farming system unit is treated as a agro-ecosystem when it attains the semblance of a forest ecosystem in species diversity and multiplicity. The adoption of sequence and mixed cropping models in the presence of compatible species of nitrogen fixing trees with or without the association of livestock components makes the agro-ecosystem benefit from the positive interaction and the stimulated cycling mechanisms. As a consequence, the system slowly achieves self-regulation and stability. Agriculture production attained at this stage will be engaging without eroding or deteriorating the natural resource base.

As the OAS derives it strength from the primary education capacity of the soil and complimentary interaction among the components of the system, the use of chemical inputs either for soil fertility management or for plant protection is excluded. This renders the system free from the pollution problems usually associated with the use of such inputs. For achieving marked improvement in soil productivity and for sustaining optimum levels of biological production, OAS lays emphasize on appropriate cropping and farming models, ensuring on-farm diversity and nutrient cycling, conservation and use of organic/biological sources of nutrients, cultural practices conducive to the conservation of soil and water resources and natural and or biological methods of pest and disease suppression.

With an understanding of the principles of organic agriculture, a straight and simple definition to the concept can be suggested. Organic agriculture is a farming system devoid of chemical inputs, in which the biological potential of the soil and underground water resources are conserved and protected from the natural and human induced degradation or depletion by adopting suitable cropping models including agro forestry and methods of organic replenishment; besides natural and biological means are used for pest and disease management by which the soil life and beneficial interaction are stimulated and sustained. The system achieves self regulation and stability as well as capacity to produce agricultural outputs at levels, which are profitable and enduring over time, and, at the same time, consistent with the carrying capacity of the managed agro-ecosystem.

There are also different opinions on nomenclature of organic farming. Some call it as ecofarming *i.e.*, farming in relation to ecosystem. Others prefer the term biological farming (farming in relation to biological diversity); yet others prefer the term bio-dynamic farming (biologically dynamic and ecologically sound and sustainable farming) or macrobiotic agriculture (agriculture in relation to macro-fauna). Whatever be the name, the basic point is that organic farming is the farming based on natural principles, which alone are sustainable. According to Fantilanan (1990), organic farming is a matter of giving back to nature what we take from it. It is safe, inexpensive, profitable and sensible. Organic farming is not mere non-chemicalism in agriculture; it is a system of farming based on integral relationship. So, one should know the relationships among soil, water, plants, and microflora and the overall relationship between plants and animal kingdom, of which, man is the apex animal. It is the totality of these relationship, which is the backbone of organic farming.

Organic farming does not totally exclude the elements of modern agriculture and varying agro climatic conditions do need input from the current technological advances. It is basically simple as it abhors excessive ploughing, hoeing, weeding and application of plant protection chemicals and fertilizers. The principal elements to be considered while practising organic farming are:

- maintaining a living soil
- making available all the essential nutrients
- organic mulching for conservation, and
- attaining sustainable high yield

Agricultural practices followed in organic farming are governed by the principles of ecology and are within the ecological means. Limited experience shows that this form of natural farming is the basis for sustainable agriculture and could be highly productive. It should not be discontinued for reversion to inefficient and less productive farming systems.

Hence, organic farming is a production system, which avoids or largely excludes the use of synthetic compound fertilizers, pesticides, growth regulators and livestock feed additives. To the maximum extent feasible, it relies on crop rotation, crop residues, animal manures, legumes, green manures, off-farming organic wastes and aspect of biological pest control to maintain soil productivity and tilth, to supply plant nutrients and to control insects, weeds and other pests. In this system most of the ill effects of modern day agriculture is avoided because:

- Use of agrochemical is forbidden.
- There is emphasis in building up of organic matter in the soil, thereby activate biological activity.
- Soil is treated as living organism.

Emphasis is given on

- Maintenance of favourable soil structure.
- Development and use of crop rotation that improves and prevents soil erosion.
- Biological control of pests, diseases and weeds.

E. Principles of organic agriculture systems

Organic agriculture systems are based on three strongly interrelated principles under autonomous ecosystem management: mixed farming, crop rotation and organic cycle optimization. The common understanding of agriculture production in all types of organic agriculture is managing the production capacity of an agro-ecosystem. The process of extreme specialization propagated by the green revolution led to the destruction of mixed and diversified farming and ecological buffer systems. The function of this autonomous ecosystem management is to meet the need for food and fibres on the local ecological carrying capacity.

(*a*) **Mixed farming:** In organic agriculture system, one strives for appropriate diversification, which ideally means mixed farming, or the integration of crop and livestock production on the farm. In this way, cyclic processes and interactions in the agro-ecosystem can be optimised, like using crop residues in animal husbandry and manure for crop production. Diversification of species biotypes and land use as a means to optimize the stability of the agro-ecosystem is another way to indicate the mixed farming concept. The synergistic concept among plants, animals, soil and biosphere support this idea.

(*b*) **Crop rotation:** Within the mixed farm setting, crop rotation takes place as the second principle of organic agriculture. Besides, the classical rotation involving one crop per field per season, intercropping, mixed cropping and under sowing are other options to optimize interactions. In addition to plant functions, other important advantages such as weed suppression, reduction in soil-borne insect pests and diseases, complimentary in nutrient demand, nutrient catching and soil covering can be mentioned.

(*c*) **Organic cycle optimisation:** Each field, farm, or region contains a given quantity of nutrients. Management should be used in such a way that optimal use is made of this finite amount. This means that nutrients should be recycled and used a number of times in different forms. Second, care should be taken that only a minimum amount of nutrients actually leave the system so that 'import' nutrients can be restricted. Third, the quantity of nutrients available to plants and animals can be increased within the system by activating the edaphon, resulting in increased weathering of parent material.

F. Concept of organic farming

It envisages a comprehensive management approach to improve the health underlying productivity of the soil. Organic farming is a matter of giving back to nature what we take from it. It is cheap, inexpensive, profitable and sensible.

G. Components of organic farming

They are (*i*) organic manures, (*ii*) non-chemical weed control measures, and (*iii*) biological pest and disease management.

1. **Organic manures:** Organic materials such as farmyard manure, biogas, slurry, composts, straw or other crop residues, biofertilisers, green manures and cover crop can substitute for inorganic fertilisers to maintain the environmental quality. In addition, the organic farmers can also use seaweeds and fish manures and some permitted fertilisers like basic-slag and rock phosphate. The use of organic manures will increase the organic matter content and water holding capacity of the soil. Erosion is reduced by organic manures. Crop rotation with legumes adds to soil fertility. Green manure provides the nutrients and improves the soil.
2. **Non-chemical weed control measures:** Compared to conventional farmers, the organic farmers use more of mechanical cultivation of row crops to reduce the weed menace. No herbicides are applied as they lead to environmental pollution.
3. **Biological pest management:** The control of insect pests and pathogens is one of the most challenging jobs in tropical and sub-tropical agriculture. Here again non-chemical, biological pest management is encouraged. The conservation of natural enemies of pests is important for minimising the use of chemical pesticides and for avoiding multiplication of insecticides-resistant pests. Botanical pesticides such as those derived from neem could be used. Selective microbial pesticides offer particular promise, of which strains of *Bacillis thuringiensis* is an example.

H. Essential characteristics of organic farming

The most important characteristics are as follows:

- Maximal but sustainable use of local resources.
- Minimal use of purchased inputs, only as complementary to local resources.
- Ensuring the basic biological functions of soil-water-nutrients-humus.
- Maintaining a diversity of plant and animal species as a basis for ecological balance and economic stability.
- Creating an attractive overall landscape, which gives satisfaction to the local people.

- Increasing crop and animal diversity in the form of polycultures, agroforestry systems, integrated crop/livestock systems, etc. to minimise risk.

Methods in organic agriculture are less intensive in terms of synthetic and other external inputs compared to the conventional farming methods, but are much more intensive from a biological point of view. Organic agriculture systems include approaches and methods like organic, biodynamic, regenerative, nature farming and permaculture. These were developed during the last 50 years. Although there are some differences among these approaches, the common understanding is that practising organic agriculture is managing the agro-ecosystem as an autonomous system, based on the primary production capacity of the soil under the given agro-climatic conditions. Agro-ecosystem management implies treating the system, on any scale, as a living organism supporting its own vital potential for biomass and animal production, along with biological mechanisms for mineral balancing, soil improvement and pest control.

I. Possibility of organic farming in India

By 2010 India needs 280 million tones of food grains and the nutrient requirement will be 34 million tones of NPK. Estimate indicates that organic residues can provide 7.1, 3.0 and 7.6 million tones of NPK respectively. Even if 50% of these organic residues are recycled, sustainable crop productivity can be achieved with less pollution and better quality food products.

J. Advantages of organic farming

- Organic manures produce optimal conditions in the soil for high yields and good quality crops.
- They supply all the nutrients required by the plant (NPK, secondary and micronutrients).
- They improve plant growth and physiological activities of plants.
- They improve the soil physical properties such as granulation and good tilth, giving good aeration, easy root penetration and improved water holding capacity. The fibrous portion of the organic matter with its high carbon content promotes soil aggregation to improve the permeability and aeration of clay soils while its ability to absorb moisture helps in the granulation of sandy soils and improves their water holding capacity. The carbon in the organic matter is the source of energy for microbes, which help in aggregation.
- They improve the soil chemical properties such as supply and retention of soil nutrients and promote favourable chemical reactions.
- They reduce the need for purchased inputs.
- Most of the organic manures are wastes or by-products, which on accumulation may lead to pollution. By way of utilizing them for organic farming, pollution is minimized.
- Organic fertilisers are considered as complete plant food. Organic matter restores the pH of the soil, which may become acid due to continuous application of chemical fertilisers.
- Organically grown crops are believed to provide more healthy and nutritional superior food for man and animals than those grown with commercial fertilisers.
- Organically grown plants are more resistant to pest and diseases, and hence few or two chemical sprays or other protective treatments are required.
- There is an increasing consumer demand for agricultural produces, which are free of toxic chemical residues. In developed countries consumers are willing to pay more organic foods.
- Organic farming helps to avoid chain reaction in the environment from chemical sprays and dusts.
- Organic farming helps to prevent environmental degradation and can be used to regenerate degraded areas.

- Since the basic aim is diversification of crops, much more secure income can be obtained than when they rely on only one crop or enterprise.

K. Limitations of organic farming

- Maintenance of organic carbon is difficult in tropical agriculture due to high temperature coupled with conventional tillage where the organic carbon is easily oxidized.
- Sudden shift to organic farming would reduce crop yields (low yields).
- Take time to buildup soil fertility and balance the ecosystem. (Organic manure and fertilizer combinely added to field increase yield doubly).
- Non-availability of organic manures, crop residues, bio-fertilizers and bio-pesticides.
- Transport of organic manures is difficult due to bulkiness.
- Absence of premium price of organic farming produces in India.
- In India, it is recognized that organic farming is expensive and labour intensive.
- Lack of technical know-how (like timely and effective control of weeds, insects and diseases).
- Lack of awareness among farmers.

Initially there may be some barriers, which inhibit the farmers from adopting organic farming. Land resources can move freely from organic farming to conventional farming; they do not move freely in the reverse direction. In changing over to organic farming an initial crop loss generally occurs, particularly if it is rapid. Organic farmers may be afraid to enter the new market without adequate government support. Hence package of practices involving organic farming practices are to be spread among the farmers and economics (cost-benefit ratio) be made available.

L. Options of organic farming

There are at least three options available in organic farming. They are:

1. Pure organic farming
2. Integrated green revolution farming
3. Integrated farming system (IFS)

1. **Pure organic farming:** Pure organic farming is done by the use of organic manures, biofertilizers and bio-pesticides and completely avoiding inorganic fertilizers and pesticides. This excludes the use of inorganics, both fertilisers and pesticides, but advocates the use of organic manures and biological pest control methods. By the year 2000 A.D., to meet the demands of the population of a billion people food production has to reach 230 million tonnes needing 24 million tonnes of NPK fertilizers and 2 million tonnes of organics. If the entire NPK requirement is to be supplied in the form of organics, either as farm or town compost or green manure, the quantity of organics required will be huge. But, large potential of organic resources remains untapped in the country. Nearly 750 million tonnes of cow dung, 250 million tonnes of buffalo manure and nearly 100–115 million tonnes of crop residues are available. The nutrient value of these organics produced annually is in the order of 2.5, 2.0 and 3 million tonnes of NPK equivalent respectively. Besides, hundreds of millions tonnes of rural and urban compost could be collected.
2. **Integrated green revolution farming:** Integrated green revolution farming is a high input technology green revolution farming involving INM and IPM. Here chemical fertilizers and pesticides are used apart from organics, bio fertilizers and bio-control agents depending on the necessity. Under this option, the basic trends of the green revolution such as intensive use of external inputs, increased irrigation, development of high yielding crop varieties and hybrids

and mechanisation of labour are retained. But much greater on the use of these inputs is obtained as to limit damage to the environment and human health. For this purpose, some organic techniques are developed and combined with the high input technology in order to create integrated systems such as 'Integrated nutrient management' (INM), 'Integrated pest management' (IPM) and biological control methods which reduce the need for chemicals. Modern biotechnology is also employed to develop higher yielding, pest resistant crop varieties. This option is possible for conditions, including fertile soils, climate and availability of necessary infrastructure facilities like irrigation.

3. **Integrated farming system:** The third option in organic farming is the low input organic farming, in which the farmers have to depend on local resources and ecological processes, recycling agricultural wastes and crop residues. Integrated Farming System (IFS) is a resource management strategy to achieve economic and sustained agricultural production through two or more interrelated or inter dependent agricultural and allied enterprises, to meet diverse requirements of the farm household, while preserving the resources base (soil fertility) and maintaining a high environmental quality. It is a Low Input Organic Farming (LIOF) in which the local resources are effectively recycled. For example, Cropping (0.96 ha); Fishery (0.04 ha) + poultry in wetlands. Crops, dairy, biogas, trees in garden lands. Crops, trees and goats in dry-farming areas.

Capital intensive green revolution techniques are simply not a feasible alternative for the poorest of the 1.4 billion farmers who live on the tropical region with ecologically, geographically and developmentally less favourable production conditions. In order to cover such risks and to ensure sustainability in their small holdings, the age-old mixed farming systems are prudently integrated with the cropping system.

M. Scope of bio-fertilizers in organic farming

In the context of search for alternate sources for sustaining soil fertility through renewable sources, harnessing of bacteria and other microorganisms for fixing N and efficient utilization of N assumes greater importance. An about 139 million tone of N per annum is fixed globally by microorganisms. Research shows that 25% of the N and P could be met through the bio-fertilizers for the cultivated crops in our country. Efforts must be taken to cover the entire cropping area with bio fertilizers by alleviating the constraints in its production and commercialization. Thus bio-fertilizers can play a significant role in the nutrient management of crops and in ushering organic farming in the near future.

N. Management of organic farming

Management of organic farming system involves:

- Organization of crop and livestock production, and the management of farm resources in such a way that it harmonizes rather than conflicts with natural systems.
- Achievement of a closed cycle to the greatest extent possible between soil, plants, animals and people and an avoidance of environmental pollution.
- Maintenance of soil fertility for optimum production, relying primarily on renewable resources.
- Reduction of pest and disease incidence through a carefully designed farm rotation and enterprise structure; use of resistant varieties; the encouragement of beneficial pest predators; and the use of other biological pest control techniques.
- Use of forms of animal husbandry which respect the welfare and behavioural needs of farm livestock.

- Use of appropriate farm machinery and cultivation techniques, which reduces non-renewable resource consumption.
- Enhancement of the environment in such a way that wildlife flourishes and it is enjoyable for people both working within the system and viewing it from outside.

These principles will lead to a wider definition of quality than is usually given to food. The following categories have been suggested:

- ***External quality*:** freedom from pest and disease damage, freshness and colour.
- ***Technological quality*:** Improved properties of storage and processing.
- ***Nutritional/physiological quality*:** Increased content of valuable nutrients such as proteins and vitamins, and the absence of detrimental substances such as nitrates and other agricultural chemical residues.
- Environmental quality of the system of production, with regard to the organisation of crop and live stock and management of farm resources, in such a way that they harmonize rather than conflict with natural systems.

17.4 INDICES OF SUSTAINABILITY

Quantification of sustainability is essential to objectively assess the impact of management systems on actual and potential productivity, and on environment. One can assess sustainability or several indices (Lal, 1994). Indices may be simple involving one parameter or complex involving several parameters. Although general principles may be the same, there indices must be fine-tuned and adapted under local environments. Some indices of sustainability include the following:

1. ***Productivity* (*P*)*:*** Production per unit of resource used can be assessed by,
   P = P/R; Where, P is productivity, P is total production and R is resource used.
2. ***Total Factor Productivity* (*TFP*)*:*** It is defined as productivity per unit cost of all factors involved (Herdt, 1993).

   $$\text{TFP} = \sum_{i=0}^{n} \frac{P}{(Ri \times Ci)}$$

   where, P is total production, R is resource used and C is cost of the resource, and n is the number of resources used in achieving total production.
3. ***Coefficient of sustainability* (*CS*)*:*** It is measure of change in soil properties in relation to production under specific management system (Lal, 1991).

   Cs = F(Oi, Od, Om) t,

   Where, Cs is coefficient of sustainability, Oi is output per unit that maximizes per capita productivity or profit, Od is output per unit decline in the most limiting or non-renewable resource, Om is the minimum assured output, and t is the time. The time scale is important and must be carefully selected.
4. ***Index of sustainability* (*Is*)*:*** It is a measure of sustainability relating productivity to change in soil and environmental characteristics (Lal, 1993; Lal and Miller, 1993).

   Is = f (Pi*Si*Wi*Ci)t,

   Where, Is index of sustainability, Si is alteration in soil properties, Wi is change in water resources and quality, Ci is modification in climatic factor and t is time.

5. ***Agricultural Sustainability*** (***Ag.***)***:*** It is a broad-based index based on several parameters associated with agricultural production (Lal, 1993)

$$As = d\ (Pt*Sp*Wt*Ct*)dt,$$

Where, As is agricultural sustainability, Pt is productivity per unit input of the limited or non-renewable resource, Sp is critical soil property of rooting depth, soil organic matter content, Wt is available water capacity including water quality, and Ct is climatic factor such as gaseous flux from agricultural activity and t is time.

17.4.1 Sustainability Coefficient (SC)

It is a complex and a multipurpose index based on a range of parameters, and is similar to As. It is defined as:

$$Sc + F\ (Pt * Pd * Pm)\ t$$

$$Sc = d(Pi * Wt* Ct)\ dt$$

Where, Pt is productivity per unit input of the limited resource, Pd is productivity per unit decline in soil property, Sc is critical level of soil property, Wt is soil water regime and quality, Ct is climatic factor, and t is time.

17.4.2 Crop Productivity as an Indicator of Sustainability

A measure of crop productivity is a good integrator of all soil, water, climatic and biotic factors. It is important to assess potential vis-à-vis actual productivity. In a science based management system, actual production exceeds potential production in soils of low inherent fertility and in harsh environments. The potential productivity, soils' productive potential within a biome, can be estimated by several models *e.g.*, CERES (Richie *et. al.,*1989) and Tropical soil Productivity calculator (Aune and Lal, 1994). If land availability is a limiting factor, appropriate indices of productivity are Land use Factor (L), Land Equivalent Ratio (LER), and Area Time Equivalent Ratio (ATER) etc.

Sustainability coefficient (***Sc***)***:*** It is a complex and a multipurpose index based on a range of parameters, and is similar to As. It is defined as:

$$Sc = f\ (Pt * Pd * Pm)t$$

$$Sc = d(Pi * Wt* Ct)\ dt$$

Where, Pt is productivity per unit input of the limited resource, pd is productivity per unit decline in soil property, Sc is critical level of soil property, Wt is soil water regime and quality, Ct is climatic factor, and *t* is time.

The Land use factor (***L***) is defined as the ratio of cropping period C plus fallow period F to cropping period C (Okigbo, 1978).

$$L = C+F/C$$

The factor L is generally high for low intensity systems *e.g.*, shifting cultivation.

The LER is calculated as follows (Willey and Osiru, 1972):

$$LER = \sum_{i=1}^{n} \left(\frac{Yi}{Ym} \right)$$

Where, Yi and Ym are yields of component crops in the inter crop and monoculture system, respectively, and n is the number of crops involved.

Because crops involved vary widely in their maturity period, ATER index considers the crop duration (Hiebsch and Mc Collum, 1987).

$$ATER = \frac{1}{t}\sum_{i=1}^{n}\left(\frac{d.Yi}{ym}\right)$$

Where, d is the growth period of the crop in days and t is the time in days for which the field remained occupied *i.e.*, the growth period of the longest duration crop. Numerical values of ATER approaches that of LER for a mixture consisting of crops of approximately identical growth periods *i.e.*, when t=dI. In comparison, productivity can also be expressed terms of the resources use efficiency of the most limiting resource *e.g*., water, nutrients, energy or labour.

17.5 INPUT MANAGEMENT FOR SUSTAINABLE AGRICULTURAL SYSTEMS

The concept of two global commonalities–biological diversity and nutrient cycling among agro ecosystems is supported by the literature on ecosystems and their management anecdotal account of indigenous practices, and the rapidly emerging literature on agro ecology. Organic matter is the basis of all bio-geo chemical cycles. The fundamental issues concerning efficient use of organic matter are leakage of nutrients from agro ecosystems and the rates of decomposition. Organic matter and the nutrients if contains are lost from soils by run off and mineralization (Tiuy, 1990), both of which can be controlled by appropriate tillage practices (Campbell *et. al.,* 1995); Lal *et. al.,* 1994). Loss of nutrients to mineralization is also controlled by assuring sufficient inputs of plant or animal material to maintain the soil organic matter (SOM) reserves (Woodmansee, 1984). Legumes are important in maintaining SOM and increasing soil N suffer. In addition, they prefect the soil from run off water and wind erosion and improve infiltration, agro forestry systems use leguminous and other trees to provide alternative crops (Steppler and Lundgren 1988), produce animal forage and fuel, recycle nutrients for crop use and project soil from wind and water erosion (Altieri, 1987).

Plant biodiversity plays an important role in pest, disease, and weed management. Crop rotations are effective in controlling pests, diseases and weeds (Altieri, 1987). Living mulches control weeds and minimize the need for herbicides (Regnion and Jahnke, 1990); Increases in structural diversity within the crop canopy leads to greater diversity in insects and less damage from insect pests (Stinner and Blair, 1990). Integration of animals into Agro ecosystems offers further diversity and stability. Mc-Infire and Cryseels (1987) summarized the potential benefits of integration of crops and animals. Integration of animals facilitates nutrients movement and increases the opportunities for efficient nutrient management across the whole farm system. Animals increase overall net productivity of the farm and reduce environmental degradation by serving as alternatives to crops on the marginal areas of farms by utilizing crop residues as feed.

17.5.1 Optimizing Nutrient Availability

A very important condition for good plant growth and health and, indirectly, for good animal and human health is the timely provision of sufficient and balanced quantities of nutrients that can be taken up by the plant roots. Nutrient deficiencies and imbalances are main constraints to crop production, especially in regions with poor and very poor or alkaline soils. There is a constant flow of nutrients through the farm. Some of the nutrients are lost by export of products, erosion, leaching and volatilization. For example, it has been estimated that in Africa nutrient losses through soil erosions and other processes exceed application of artificial fertilizers (Stocking, 1986). If the farm is to remain productive it must be ensured that the amount of nutrients leaving the farm does not exceed the amount returned to it. In other words, over time, there must be a positive nutrient balance.

17.5.2 Micronutrient Deficiencies

Due to intensive cropping the micronutrients are removed to a considerable extent, which control various aspects of plant growth. A study at Ranchi, India revealed that applying looks NPK (10:25:25) per ha. Led to depletion of Zinc by 0.619/ha and copper by 0.49/ha. this can depress yields by up to 4t/ha in rice, 2 t/ha in wheat and 3.4 t/ha in maize. Also iron is a limiting factor in rice production in the new rice-wheat rotation evolved in the non-traditional rice growing areas of Punjab. One of the solutions to correct this micronutrient deficiencies is greater use of organic manures and multiple cropping with legumes. At Punjab Agricultural University, Ludhiana field experimental results proved that application of poultry manure, pig manure and farmyard manure were effective in meeting zinc requirements in a maize-wheat rotation. Also cultural practices such as prolonged submergence of the field can be used to tackle iron and manganese deficiencies (Sharma, 1985).

17.5.3 Limiting Nutrient Losses

Nutrient losses can be limited by:

- Recycling organic wastes by returning them to the field, either directly or treated (composted, fermented etc.).
- Applying organic and artificial fertilizers in such a way that nutrients are not leached by excessive rain or volatilized by high temperature or solar radiation.
- Reducing losses due to run-off and soil erosion.
- Minimizing nutrient losses due to biomass bussing.
- Reducing volatilization of nitrogen by denitrification under wet soil conditions.
- Avoiding leaching by using organic and artificial fertilizers, which release nutrients slowly, maintaining high humus content in the soil and intercropping plant species with different rooting depth.
- Limiting nutrient export in products by producing crops with relatively high economic value relative to nutrient content.

17.5.4 Use of Chemical Fertilizers

The use of chemical fertilizers is essential for obtaining high crop yields. However, many small landholders and resource-poor farmers cannot offer costly fertilizers. Most soils in the tropics are so deficient in primary nutrients that it is imperative that strategies be developed for adding them from outside the ecosystem. There is some potential for enhancing N supply by biological N fixation. Additional N and other nutrients must be supplied. The requirements for chemical fertilizers, however, can be reduced considerably by decreasing losses, recycling nutrients and through biological N fixation.

17.5.5 Nutrient Recycling

Nutrient recycling or regime is an important strategy for sustainable crop production. It involves returning nutrients removed by crops to the soil for further use. In addition, soil fauna (*e.g.,* earth worms, termites) also play an important role in recycling of plant nutrients. Growing deep-rooted crops is important in order to recycle nutrients from the sub soil by returning them through crop residue to the surface where the succeeding shallow rooted crops can use them. Use of mulches, incorporation of crop residues and animal waste, growing legumes as intercrops in cereals etc., can substantially reduce chemical fertilizer requirements.

17.5.6 Use of Crop Residues

Crop residues contain substantial quantities of plant nutrients. The beneficial effects of returning crop residues as mulch on crop yields are well known (Akimbo and Lal, 1980 and Kang, 1993). These benefits are not only to the recycling of plant nutrients but also to improvements in soil moisture and temperature, enhancement of soil structure and soil erosion control. The nutrient composition of the crop residues of some of the important crops is given in Table 17.2.

Table 17.2. Nutrient Composition (%) of Crop residues of Major Crops grown in the tropics

Crop/Species	*N*	*P*	*K*
Cowpea straw	1.07	1.14	2.54
Cowpea leaves	1.99	0.19	2.20
Rice	0.58	0.10	1.38
Maize	0.59	0.31	1.31
Oil palm (Processed fiber)	1.24	0.10	0.36
Sesbania leaves	4.00	0.19	2.00
Crotalaria spp	2.89	0.29	0.72
Tephrosia spp	3.73	0.28	1.78
Azolla spp	3.68	0.20	0.11
Typha spp	1.37	0.21	2.38
Water hyacinth	2.04	0.37	3.40

Source: FAO, 1990.

17.5.7 Biological Nitrogen Fixation

Augmenting the nitrogen supply to crops through biological nitrogen fixation is a viable officer for resource–poor farmers of the tropics. The amount of N fixed by legumes can range from 20–250 kg/ha/yr depending

Table 17.3. Quantities of N field by various Legume Crops

Crop species	*N fixed (kg/ha/yr)*
Alfalfa	78–222
Peanut	87–222
Cowpea	65–130
Field peas	174–195
Soybean	170–217
Birds foot	49–112
Chickpea	24–84
Common bean	70–124
Faba bean	77–250
Vetch	111
Ladino clover	164–187
Lentil	167–188
White lupin	193–247
Sesbania spp.	267

on the species, soil type, climate and agro-eco-region. Some common legumes that can be grown as cover crops and the quantity of N fixed by these crops are listed in Table 17.3.

17.5.8 Use of Biofertilizers

Biofertilizers have been recognized as important inputs in integrated plant nutrition systems. The use of legume green manure, blue green algae and Azolla for rice: Azotobacter and Azospirillum for wheat, millets and vegetable crops; Rhizobium for pulses and oil legume crops, Phosphate solubilizers Vesicular Arbuscular Mycorrhizae) for various crops is well reported, on an average these biofertilizers can minimize the use of inorganic N by 25–50 kg/ha.

17.5.9 Green Manuring

The green manure crops when applied improve the physical and chemical properties of the soil. Green manures also increase the fertilizer use efficiency of crops when applied in combination with inorganic fertilizers. Among the green manure crops, special attention is being given to *Sesbania rostrata*, which bears stem nodules in addition to the root nodules. The amount of N contributed in terms of fertilizer N equivalence ranges from 80–120 kg/ha. In a field trial comprising different green manure crops, it was found out that *Sesbania rostrata* produced the highest biomass (20–25 tons/ha) and accumulated a maximum of 150–220 kg N/ha. More details are given in the chapter 15. The common leguminous green manure crops used in tropics and their N content are given in Table 17.4.

Table 17.4. Common Green Manure Crops and their N content

Crop species	*Scientific name*	*Biomass*	*N per cent (Moist)*
Sunnhemp	*Crotalaria juncea*	21.2	0.43
Dhaincha	*Sesbania aculeata*	20.0	0.43
Dhaincha	*Sesbania rostrata*	19.6	–
Pillipesara	*Phaseolus trilobus*	18.3	1.10
Mungbean	*Phaseolus arvensis*	8.0	0.53
Cowpea	*Vigna sinensis*	15.0	0.49
Guar	*Cyamposis tetragonoloba*	20.0	0.34
Senji	*Melilotus alba*	28.6	0.57
Khesari	*Lathyrus sativus*	12.3	0.54

Annexures

ANNEXURE-1

Units related to Crop Production

A. AREA

Inch: It is equal to 2.54 cm.

Foot: It is equal to 30.48 cm or 0.305 m.

Cent: It is a unit of measurement of an area of land, which is 1/100 of an acre. This is equal to 40 m^2 or 435.6 sq. ft.

Area: A unit of measurement of an area to 100 cents (4000 m^2). It is also equal to 2/5th of hectare.

Hectare: It refers to an area of 10,000 m^2 or 250 cents or 2.5 acres.

100 kuzhi = 1 maa or kaani; 3 maa = 1 acre; 20 maa = 6.67 acres = 1 veli.

B. WEIGHT

Pound : It is a unit of weight equal to 454 grams.

Kilogram : It is unit of weight equal to 1000 grams or 2.203 pounds.

Quintal : This refers to a unit of weight equal to 100 kg or 0.1 tonne.

Bale : 177.8 kg (cotton lint).

Tonne : Unit of weight equal to 1000 kg or 10 quintals.

Million tonnes : 10,00,000 tonnes.

C. VOLUME

Milli litre (ml) : It is a unit of volume equal to 1/1000th of a litre. 1 ml = 1 cc = 1cu. mm.

Litre : It is a volume equal to 1000 ml or 1000 cc.

Cubic meter : It is a volume equal to 1000 litres.

Cubic foot : It is a volume equal to 28.32 litres.

TMC : Thousand metric cubic feet.

Imp. gallon : 4.546 litres.

APPLICATIONS OF REMOTE SENSING IN AGRICULTURE

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Agricultural products from crops form a large part of every persons diet. Producing food of sufficient quantity and quality is essential for the well-being of the people anywhere in the world. Agricultural plants, as living organisms, require water and nutrients in order to grow and are sensitive to extreme weather phenomena, diseases and pests. Remote sensing can provide data that help identify and monitor crops. When these data are organized in a Geographical Information System along with other types of data, they become an important tool that helps in making decisions about crops and agricultural strategies.

The term "remote sensing," first used in the United States in the 1950s by Ms. Evelyn Pruitt of the U.S. Office of Naval Research. Remote sensing refers to the activities of recording/ observing/perceiving (sensing) objects or events at far away (remote) places. According to Aronoff (1995), "Remote sensing is the art and science of obtaining information from a distance, i.e. obtaining information about objects or phenomena without being in physical contact with them. The science of remote sensing provides the instruments and theory to understand how objects and phenomena can be detected. The art of remote sensing is in the development and use analysis techniques to generate useful information". In remote sensing, the sensors are not in direct contact with the objects or events being observed. http://www.crisp.nus.edu.sg/~research/tutorial/earth.htm The information needs a physical carrier to travel from the objects/events to the sensors through an intervening medium. The electromagnetic radiation is normally used as an information carrier in remote sensing. The output of a remote sensing system is usually an image representing the scene being observed. A further analysis and interpretation is required in order to extract useful information from the image and applying that information.

The components of Remote Sensing are

Energy Source: The first requirement for remote sensing is an energy source which provides electromagnetic energy.

Radiation and the Atmosphere: As the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes through. This interaction may take place a second time (active remote sensing) as the energy travels from the target to the sensor.

Interaction with the Target: once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation.

Recording of Energy by the Sensor: after the energy has been reflected by, or emitted from the target, we require a sensor (remote-not in contact with the target) to detect and record the electromagnetic radiation.

Transmission, Reception, and Processing: The energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image.

Interpretation and Analysis: The processed image is interpreted, visually or digitally, to extract information about the target.

Application: The final element of the remote sensing process is achieved when we apply the information we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem.

Principle of Remote Sensing: The basic principle of remote sensing is that different objects based on their structural, physical or chemical properties reflect or emit different amount of energy in different wavelength ranges of electro-magnetic spectrum. The sensors measures the amount of energy reflected from that object and represents it through an image.

Types of Remote Sensing

Active Remote Sensing: when remote sensing work is carried out with a man made source of radiations which is used to illuminate a body and to detect the signal reflected form. eg. Radar and Lidar remote sensing.

Passive Remote Sensing: when remote sensing work is carried out with the help of electromagnetic radiations (signals) reflected by a natural body (sun and earth). eg visible, NIR and Microwave remote sensing. Nowadays, remote sensing is employed in precision agriculture to manage and monitor farming practices at different levels. The data can be used to farm optimization and spatially-enable management of technical operations. The images can help determine the location and extent of crop stress and then can be used to develop and implement a spot treatment plan that optimizes the use of agricultural chemicals. National governments can use remote sensing data, in order to make important decisions about the policies they will adopt, or how to tackle national issues regarding agriculture. Individual farmers can also receive useful information from remote sensing images, when dealing with their individual crops, about their health status and how to deal with any problems.

Applications of Remote Sensing in Agriculture

Crop Identification: It is very important for a national government to know what crops the country is going to produce in the current growing season. This knowledge has financial benefits for the country, as it allows the budget planning for importing and exporting of food products. In order to identify a particular crop, we need to be familiar with its growth cycle (germination, growth, pollination, senescence). Some crops last for a couple of months, other need more than 6 months to complete their growth. In addition we need to know in advance, how the crops reflect the near-infrared at each of their various growth stages. Using the different near infrared reflectance is one of the tools we have to discriminate between two crops. Having the knowledge of when each crop is planted and harvested, we can estimate the percentage of vegetation cover through the growth period, assuming no external factors (stress, disease, etc.) affect its growth. By using multi-date data (data from different dates) from one growing period, it is possible to identify the different crop types, because the vegetation cover of each crop changes at different rates. By combining this information with remote sensing data, we can discriminate between different crops and also identify them. This information serves to predict grain crop yield, collecting crop production statistics, facilitating crop rotation records, mapping soil productivity, identification of factors influencing crop stress, assessment of crop damage and monitoring farming activity.

Identifying Stressed Plants: Chlorophyll is an essential part of the process of photosynthesis. It absorbs solar energy in order to provide power for the process of photosynthesis. Because it absorbs energy, it has an important effect on the amount of energy that is reflected. With remote sensing we can directly estimate how much chlorophyll there is in a plant. By combining more than one bands of the recorded remote sensing data, we can create vegetation indices and use them to estimate crop status. Depending on the visible and near-infrared reflectance, the produced vegetation indices give us an indication on the amount of chlorophyll present in the plants. With this information we can estimate if and how much stress the plants are under.

Before chlorophyll starts to break down in stressed plants, whatever is causing the stress has already started to affect the cellular structure of the leaves. This affects the plant reflectance in the near infrared, even before the loss of chlorophyll changes the reflectance in the visible region. With remote sensing we can see the changes in the near infrared (which are not visible to our eyes) before the chlorotic symptoms appear, and this way we can have an early warning that the plants are under stress. Using vegetation indices with data from sensors with a very high spatial resolution (below 10 metres and even down to a metre), we can also see areas of the fields where crops suffer from some kind of stress, and estimate how serious it is. Being able to identify stress variations within a field allows the farmer to locate the problem and take appropriate action in order to deal with the problem at the specific location. Therefore, remote sensing allows detection of environmental stresses in crops, such as shortage of water and irrigation, chlorosis, nitrogen deficiency. Hyperspectral imaging allows monitoring of crop health and detection of nutrient deficiency (i.e. NPK).

Like many organisms, plants require water to survive. In addition to the water being used in essential biochemical processes, water is the "means of transportation" for nutrients from the soil to every part of the plant. Water enters the plant through the roots, travels through the main stalk and the branches, eventually reaching the leaves. From there, through the leaf pores known as stomata, it is released in the atmosphere. This process is known as transpiration. All the biological processes taking place within a plant produce heat. The transpiring water captures that heat and removes it from the plant when it transpires through the leaves. When there is not enough water and the plant is under stress, it cannot lose heat through transpiration fast enough and as a result, the plant's temperature increases. This increase in temperature can be detected with remote sensing, by using parts of the spectrum that are sensitive to heat.

One of the problems with this method is partial vegetation cover. When vegetation does not completely cover the soil, the soil temperature is affecting the thermal signal recorded by the sensor. When this happens it is easy to confuse low vegetation cover with hot soil with water stress. However if we have an idea of the amount of vegetation, and particularly the amount of leaf surface per unit of ground area (what is known as leaf area index), we can correct the measurement and reduce the effect of any soil influence. A crop evapo-transpiration rate decrease is an indicator of crop water stress or other crop problems such as plant disease or insect infestation. Remote sensing images have been combined with a crop water stress index ("CWSI") model to measure field variations (Moran *et al.,* 1997).

Detection, Diagnosis and Control of Plant Diseases: In addition to identifying plants under stress from lack of nutrients or water, remote sensing can also assist in protecting the plants from potential attacks of pests, fungi or bacteria. By combining agricultural knowledge with remotely sensed data, it is possible to have early warning and prevent a pest or a disease from affecting the crops, by taking appropriate action at an early stage. Hyper-spectral remote sensing helps to detect crops diseases at early stages and facilitates the targeted delivery of the necessary treatments. Detection of diseases at early stage is a lot easier less costly than currently used impractical human scouting techniques. It is also possible to assess the extent of the damage caused by pests and diseases, by using similar methods to those used to identify stressed plants. The symptoms of such attacks usually cause the break-down of chlorophyll, and we can identify the reduction of chlorophyll concentration in the plants through remote sensing. In addition to loss of chlorophyll, pest and diseases can cause the destruction of whole leaves. This leads to a reduction in the total leaf area and as a result, the reduction of the plant's capacity for photosynthesis. As we are able to estimate the Leaf Area Index (LAI) of a group of plants, it is possible to identify an insect attack at an early stage and warn the farmers to take the appropriate measures. The study conducted by Apan *et al.* (2004) demonstrated that Hyperion satellite hyperspectral imagery could be used to detect orange rust (*Puccinia kuehnii*) disease in sugarcane.

Yield Estimation: Remote sensing has been used to forecast crop yields based primarily upon statistical–empirical relationships between yield and vegetation indices (Thenkabail *et al.*, 2002; Casa and Jones, 2005). Information on expected yield is very important for government agencies, commodity traders and producers in planning harvest, storage, transportation and marketing activities. The sooner this information is available, the lower the economic risk, translating into greater efficiency and increased return on investments.

Because of the particular manner vegetation reflects the electromagnetic radiations, we can assess the crop status by using remote sensing data. By combining these data with additional data (such as the climatic conditions) in complex models, it is possible to estimate the final yield of a crop field at a very early stage. Remote sensing data and the derived vegetation indices can be used to make estimates of crop yield, provided that a relationship between the index or indices and crop yield for the particular crop in the specific location has been established in the past. These are only rough estimates and are not 100% reliable. More accurate predictions require the use of models that combine those indices with ancillary data, such as meteorological data, farming practices, soil properties etc.

For instance, reflectance from both individual leaves and plant canopies in the visible portion of the spectrum of electromagnetic radiation is low because of the absorption properties of pigments while in the near-infrared (NIR) is high since live vegetation strongly scatter in these wavelengths. Total reflectance from crops in the red and NIR wavelengths is very strongly related to plant biomass and the degree of soil cover, which are closely linked with a yield. Knowing the amount of the biomass, determined on the basis of spectral data gathered at different phenological stages, it is possible, with varying degree of probability to estimate a yield. The relationship between spectral data and yield depends largely on the time in which these data are collected and generally, the strongest correlation occurs when plant biomass is the greatest. So, it allows estimation of yield early in the season and plan harvesting accordingly, monitoring of crop biomass and development in real time using different indices (NDVI, leaf area index, leaf chlorophyll content).

Yield Maps: Spatial distribution of plant biomass and other bio-physical parameters within fields is usually not even, but very patchy, defined by soil conditions, therefore it is possible to compile yield maps. Such maps created on the basis of satellite images acquired in many seasons represent the spatial variability in crops yield regardless of plant species. Yield maps are applied to determine patterns of fertilization and irrigation, and indirectly, can be used in planning programs for the eradication of weeds, pests and plant diseases. In such programs, fertilizer or pesticides doses are adopted to the productivity of a specific spot on the field. Apart from economic profits to the farmer, environmental benefits are also important that rely on reducing the negative impact of agriculture production inputs on the environment.

Plant Breeding Research: Plant breeders and other researchers employ many different scientific methods in their traditional or molecular-based programs, ranging from direct measurement of grain or seed production to more complex marker-assisted techniques. Near Infrared (NIR) spectroscopy provides the agricultural researcher with a non-destructive tool for plant, seed, and other agricultural product analysis. Once calibration models have been developed a single sample can be measured in less than one minute. NIR is ideal for plant breeding applications since most breeding programs have thousands of nursery entries that require analysis in very compressed timeframe. NIR can also be used at plant breeding facilities by less experienced operators than would be possible with traditional analytic methods. When applied to plant breeding and agricultural research, NIR analysis significantly reduces the time and financial resources required to produce a new variety, sometimes eliminating years from the development cycle. NIR spectroscopy is rapid and cost-effective for plant and seed analysis compared to conventional wet chemistry and HPLC methods.

In the past several years there has been a considerable increase in the use of NIR spectroscopy for rapid determination of constituent concentrations and quality parameters in agricultural products. Common applications for NIR include analysis of seed/grain composition and feed and food composition. Vegetative indices and the same type of quantitative modeling techniques used to develop soil nutrient calibrations have been used by researchers for determination of a wide range of plant bio-chemicals, including chlorophyll, xanthophylls (and other pigments), lignin, cellulose, and total nitrogen content (as related to protein concentration). In addition to analysis of photosynthetic biomass, these methods have also been applied to rapid analysis of seed composition for crops such as corn, wheat, rice, soybeans, and canola.

Soil Analysis: For decades, scientists have used high-resolution reflectance spectra of minerals and soils to determine soil mineralogy, and to assess soil physical properties. A major breakthrough in these studies has been the use of visible-near infrared spectroscopy to develop quantitative calibrations for rapid characterization of soil nutrients and various physical properties of soils. The coupling of this technology with remote sensing data, geo-referenced ground surveys, and new spatial statistical methods has resulted in the improved capability for large area soil assessments. Rapid spectroscopic soil analysis breaks the bottleneck of sample collection and lab testing, and permits the assessment of soil quality on a large number of representative samples covering expansive geographic areas. These studies overlap into many practical applications, including environmental applications, agricultural analysis, hydrology, and soil fertility assessment.

Soil Mapping: Soil maps are another type of maps developed using remote sensing data. These maps can be compiled on the basis of airborne or satellite images acquired when the degree of soil coverage by plants is less than 30-50%. Soil maps present homogeneous soil zones with similar properties and conditions for plant growth. These maps are useful in determining soil sampling locations for detailed studies of soil, soil moisture sensors location or developing irrigation plans.

The disturbance of soil by land use has impacts on the quality of our environment. Salinity, soil acidification and erosion are some of the problems. Remote sensing is a good method for mapping and prediction of soil degradation. Soil layers that rise to the surface during erosion have different color, tone and structure than non eroded soils thus the eroded parts of soil can be easily identify on the images. Using multi-temporal images we can study and map dynamical features - the expansion of erosion, soil moisture.

Land Cover Mapping: It is one of the most important and typical applications of remote sensing data. Land cover corresponds to the physical condition of the ground surface, for example, forest, grassland, concrete pavement etc., while land use reflects human activities such as the use of the land, for example, industrial zones, residential zones, agricultural fields etc Initially the land cover classification system should be established, which is usually defined as levels and classes. The level and class should be designed in consideration of the purpose of use (national, regional or local), the spatial and spectral resolution of the remote sensing data, user's request and so on. Information on land cover and changing land cover patterns is directly useful for determining and implementing environment policy and can be used with other data to make complex assessments (e.g. mapping erosion risks).

Land cover change detection is necessary for updating land cover maps and the management of natural resources. The change is usually detected by comparison between two multi-date images, or sometimes between an old map and an updated remote sensing image.

Seasonal: agricultural lands and deciduous forests change seasonally

Annual: land cover or land use changes, which are real changes, for example deforested areas or newly built towns.

Precision Agriculture: Precision agriculture is a collection of agricultural practices that focus on specific areas of the field at a particular moment in time. This is opposed to more traditional practices where the various crop treatments, such as irrigation, application of fertilizers, pesticides and herbicides were evenly applied to the entire field, ignoring any variability within the field. Advances in remote sensing technology and the reduced cost of sensors is now allowing for the more widespread use of such equipment in farming. With the use of these sensors it is possible to identify which particular areas of the field are in need of which treatment, and focus the application of chemicals to these particular locations alone, reducing the amount of chemicals used, and thus the cost of the application, as well as protecting the environment.

Remote sensing imagery collected from satellites, does not have any geographical information associated with the spectral data. This means that we do not actually know the exact location on the Earth that each pixel of the image represents. This information must be inserted manually through a processing method called Geometric Correction, which also corrects geometric errors within the image. Data collected in the field are recorded by sensors which are mounted on the tractor and scan the field as the tractor moves forward, collecting data sequentially (in rows). In order to assign geographic co-ordinates to each spectral measurement, the co-ordinates of the tractor are frequently recorded through the Global Positioning System (GPS). Since Precision Agriculture is dealing with individual small sized portions of the field, very high spatial accuracy is required.

By measuring the reflectance of the plants at various wavelengths, it is possible to collect a lot of information about the status of the plants. From previous research, there are known relationships between the indices using those two regions of the spectrum and the amount of vegetation, a measure of which is the Leaf Area Index. From these estimates we can derive the population of the plants. The data provided by the sensors can also be used to make an estimate on the future crop yield. By calculating the Normalised Difference Vegetation Index (NDVI), or the Soil-Adjusted Vegetation Index (SAVI) when vegetation cover is low, we can get information on the crops' vigour. A lot of research has been done to derive relationships between a vegetation index of a crop, measured at a particular time, and the final crop yield. These relationships can be used to help estimate the final crop yield, using the data collected by the sensors on-board the tractors. Each of these relationships, however, is usually only applicable for a particular crop, grown at a specific region and the remotely sensed data need to have been collected at a particular moment during the growth period. By identifying the location of plants that are not growing at the expected rate, and have a lower Leaf Area Index than expected, the farmer can decide which areas of the field should receive particular attention in terms of the application of fertilizers. The same is true concerning the need for pesticides. Weeds can have very different spectral signature, compared with the crop and remote sensing can be used to identify their location. It is quite common for the weeds to be scattered in the field. On the other hand, pests like fungi and bacteria, tend to appear at the edge of the field and slowly spread throughout the field. By using remote sensing and GPS, it is possible to identify the exact location where the application of fertilizers or pesticides is required. The Variable Rate Treatment (VRT) is a system that regulates the rate of pesticides or fertilizers, releasing only the required amount over the areas or the field that are in need of the chemicals. Many of the pesticides and fertilizers that enter the field are transferred to other areas through evaporation, surface leeching or seeping in the ground and get transferred with underground water. The use of VRT greatly reduces the amount of chemicals that are applied in the field. This leads to lower cost for the farmer, since less quantity is required, and also has a reduced effect to the environment. There are numerous examples of the use of the satellite images for the estimation of nitrogen status of crops. For example, Bausch and Khosla (2010) demonstrated that the satellite multi-spectral data could be used for an accurate assessment of the within field spatial variability of nitrogen status of maize for in-season nitrogen management.

In addition to pesticides and fertilizers, water is becoming a very valuable commodity as good quality water is becoming less and less available around the world. Saving on water with the use of variable-rate treatments is already important and will become even more significant in the years to come. Lack of nutrients or water at a specific location in the field is dealt with the application of the appropriate fertilizer, or the adjustment of the irrigation scheme. Precision farming can accurately identify the variability and its cause, quantify the variability and its scale, record it and its location and map it so it can be managed. Threats by weeds or attacks by other organisms are identified early and are dealt with at the isolated locations and not in the whole field.

Conclusion: The chapter demonstrates the strong role remote sensing plays within the agricultural sector. Requests for objective information will increase in the future, as a result of the expected changes in the agricultural sector (e.g., meeting food requirements and environmental restrictions). For example, for most crops, large production increases (between 45 and 70%) are possible from closing yield gaps to 100% of attainable yields (Mueller *et al*., 2012). Data collected from remote sensing facilitate monitoring weed infestations, damages caused by pests and plant pathogens, thereby making it possible to counteract quickly. The ability to use remote sensing data to determine fertilization needs of plants based on the nutrient content of crops and soils helps to increase yields and improve the quality of harvested seeds and fruits, which is important for improving the crop profitability. Accurate determination of the nutritional requirements of plants at critical stages during the field season helps to optimize fertilization as well as reduce potential adverse impacts associated with offsite transport of agrochemicals. Remote sensing has also been used to assess the water needs of plants and determine the date of commencement of irrigation, making it easier to manage crop production under conditions of water stress.

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Chapter 5

PRECISION AGRICULTURE

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Background

An agricultural production system is the outcome of a complex interaction of seed, water and agro-chemicals including fertilizers and pesticides. Therefore, careful management of all inputs is essential for the sustainability of such complex system. The focus on enhancing the productivity without considering the ecological impacts of the input resources has resulted into environmental degradation. Application of technologies to improve nitrogen management has been shown to have a positive impact on reducing nitrogen application, improving yield of grain and sugar in sugar beets and sugarcane, increasing profitability, and decreasing the negative effect from excess nitrogen in the environment. The productivity can be increased without any adverse effect by maximizing the resource input efficiency. It is also certain that availability of labor for agricultural activity is going to be in short supply in future. The time has now arrived to bring information technology and agricultural science together for improved economic and environmentally sustainable crop production. This gives birth to Precision Farming.

History

Precision agriculture is a key component of the third wave of modern agricultural revolutions. The first agricultural revolution came along during the advent of increased mechanization, from 1900-1930. Each farmer produced enough food to feed about 26 people during this time. The 1990s prompted the Green Revolution with new methods of genetic modification, which led to each farmer feeding about 155 people.It is expected that by 2050, the global population will reach about 9.6 billion, and food production must effectively double from current levels in order to feed every mouth. With new technological advancements in the agricultural revolution of precision farming, each farmer will be able to feed 265 people on the same acreage.Around the world, precision agriculture developed at a varying pace. Precursor nations were the United States, Canada and Australia. In Europe, the United Kingdom was the first to go down this path, followed closely by France, where it first appeared in 1997-1998. In Latin America the leading country is Argentina, where it was introduced in the middle 1990s with the support of the National Agricultural Technology Institute. Brazil established a state-owned enterprise, Embrapa, to research and develop sustainable agriculture. The development of GPS and variable-rate spreading techniques helped to anchor precision farming management practices (Simon Blackmore, 2016). Today, less than 10% of France's farmers are equipped with variable-rate systems. Uptake of GPS is more widespread, but this hasn't stopped them using precision agriculture services, which supplies field-level recommendation maps.

Overview

The first wave of the precision agricultural revolution will come in the forms of satellite and aerial imagery, weather prediction, variable rate fertilizer application, and crop health indicators. The second wave will aggregate the machine data for even more precise planting, topographical mapping, and soil data.

Precision agriculture aims to optimize field-level management with regard to:

- Crop science: by matching farming practices more closely to crop needs (e.g. fertilizer inputs);
- Environmental protection: by reducing environmental risks and footprint of farming (e.g. limiting leaching of nitrogen);

- Economics: by boosting competitiveness through more efficient practices (e.g. improved management of fertilizer usage and other inputs).

Precision agriculture also provides farmers with a wealth of information to:

- Build up a record of their farm;
- Improve decision-making;
- Foster greater traceability
- Enhance marketing of farm products
- Improve lease arrangements and relationship with landlords
- Enhance the inherent quality of farm products (e.g. protein level in bread-flour wheat)

Introduction

Precision agriculture (**PA**) or **satellite farming** or **site specific crop management** (**SSCM**) is a farming management concept based on observing, measuring and responding to inter and intra-field variability in crops. The goal of precision agriculture research is to define a decision support system(DSS) for whole farm management with the goal of optimizing returns on inputs while preserving resources (McBratney et al. 2003; Whelan &McBratney, 2003).
Among these many approaches is a phytogeomorphological approach which ties multi-year crop growth stability/characteristics to topological terrain attributes. The interest in the phytogeomorphological approach stems from the fact that the geomorphology component typically dictates the hydrology of the farm field.(Howard & Mitchell, 1985; Kasparet al. 2003)

The practice of precision agriculture has been enabled by the advent of GPS and GNSS. The farmer's and/or researcher's ability to locate their precise position in a field allows for the creation of maps of the spatial variability of as many variables as can be measured (e.g. crop yield, terrain features/topography, organic matter content, moisture levels, nitrogen levels, pH, EC, Mg, K, etc.)(McBratney et al., 2005).Similar data is collected by crop yield monitors mounted on GPS-equipped combine harvesters, arrays of real-time vehicle mountable sensors that measure everything from chlorophyll levels to plant water status, multi-, and satellite imagery. This data is then used by variable rate technology (VRT) including seeders, sprayers, etc. to optimally distribute resources.

Precision agriculture has also been enabled by affordable unmanned aerial vehicles like the DJI Phantom that cost under $1000 and can be operated by novice pilots. These systems, commonly known as drones, can be equipped with hyperspectral or RGB cameras to capture many images of a field that can be processed using photogrammetric methods to create orthophotos and NDVI maps (Chris Anderson, 2014).

Definitation of Precision Agriculture

Precision Agriculture is the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for improving production and environmental quality.
The success in precision agriculture depends on the accurate assessment of the variability, its management and evaluation in space-time continuum in crop production.

The agronomic feasibility of precision agriculture has been intuitive, depending largely on the application of traditional arrangement recommendations at finer scales.

The agronomic success of precision agriculture has been quite convincing in crops like sugar beet, sugarcane, tea and coffee.

The potential for economic, environmental and social benefits of precision agriculture is largely unrealized because the space-time continuum of crop production has not been adequately addressed.

The Need for Precision Farming

The 'Green revolution' of 1960's has made our country self sufficient in food production. In 1947,the country produced a little over six million tonnes of wheat, in 1999;our farmers harvested over 72 million tonnes, taking the country to the second position in wheat production in the world. He production of food grains in five decades, has increased more than threefold, the yield during this period has increased more than two folds. All this has been possible due to high input application, like increase in fertilization, irrigation, pesticides, higher use of HYV's, increase in cropping intensity and increase in mechanization of agriculture.

i) Fatigue of Green Revolution

Green revolution of course contributed a lot. However, even with the spectacular growth in the agriculture, the productivity levels of many major crops are for below than expectation. We have not achieved even the lowest level of potential productivity of Indian high yielding varieties, whereas the world's highest productive country have crop yield levels significantly higher than the upper limit of the potential of Indian HYV's. Even the crop yields of India's agriculturally rich state like Punjab is far below than the average yield of many high productive countries (Ray *et al*., 2001).

ii) Natural Resource Degradation

The green revolution is also associated with negative ecological/environmental consequences. The status of Indian environment shows that, in India, about 182 million ha of the country's total geographical area of 328.7 million ha is affected by land degradation of this 141.33 million ha are due to water erosion, 11.50 million ha due to wind erosion and 12.63 and 13.24 million ha are due to water logging and chemical deterioration (salinisation and loss of nutrients) respectively. On the other end, India shares 17 per cent of world's population, 1 per cent of gross world product, 4 per cent of world carbon emission, 3.6 per cent of CO_2 emission intensity and 2 per cent of world forest area. One of the major reasons for this status of environment is the population growth of 2.2 per cent in 1970 – 2000.The Indian status on environment is, though not alarming when compared to develop countries, gives an early warning.

In this context, there is a need to convert this green revolution into an evergreen revolution, which will be triggered by farming systems approach that can help to produce more from the available land, water and labour resources, without either ecological or social harm. Since precision farming, proposes to prescribe tailor made management practices, it can help to serve this purpose.

THE PRECISION FARMING SYSTEM CONCEPT

PFS is based on the recognition of spatial and temporal variability in crop production. Variability is accounted for in farm management with the aim of increasing productivity and reducing environmental risks. In developed countries, farms are often large and comprise several fields. The spatial variability in large farms, therefore, has two components: within-field variability and between-field variability. The precision farming system within a field is also referred to as site-specific crop management (SSCM).

SSCM refers to a developing agricultural management system that promotes variable management practices within a field according to site or soil conditions.

However, according to Batte and VanBuren (1999), SSCM is not a single technology, but an integration of technologies permitting:

- collection of data on an appropriate scale at a suitable time;
- Interpretation and analysis of data to support a range of management decisions; and
- Implementation of a management response on an appropriate scale and at a suitable time.In a study of PFS in developed countries,Segarra (2002) highlights the following advantages to farmers:

- **Overall yield increase.**The precise selection of crop varieties, the application of exact types and doses of fertilizers, pesticides and herbicides, and appropriate irrigation meet the demands of crops for optimum growth and development. This leads to yield increase, especially in areas or fields where uniform crop management practices were traditionally practised.

- **Efficiency improvement**. Advanced technologies,including machinery, tools and information, help farmers to increase the efficiency of labour, land and time in farming. In the United States, a mere 2 hours are sufficient to grow 1 ha of wheat or maize.

- **Reduced production costs**. The application of exact quantities at the appropriate time reduces the cost of agrochemical inputs in crop production. In addition, the overall high yield reduces the cost per unit of output.

- **Better decision-making in agricultural management.** Agricultural machinery, equipment and tools help farmers acquire accurate information, which is processed and analysed for appropriate decision making – in land preparation, seeding, fertilizer,pesticide and herbicide application, irrigation and drainage, and post-production activities.

- **Reduced environmental impact.** The timely application of agrochemicals at an accurate rate avoids excessive residue in soils and water and thus reduces environmental pollution.

- **Accumulation of farmers' knowledge for better management with time.** All PFS field activities produce valuable field and management information and the data are stored in tools and computers.Farmers can thus accumulate knowledge about their farms and production systems to achieve better management.

NEW TOOLS AND EQUIPMENT

Global positioning system (GPS)

GPS is a navigation system based on a network of satellites that helps users to record positional information (latitude,longitude and elevation) with an accuracy of between 100 and 0.01 m (Lang, 1992).GPS allows farmers to locate the exact position of field features,such as soil type,pest occurrence,weed invasion,water holes,boundaries and obstructions.There is an automatic controlling system,with light or sound guiding panel (DGPS), antenna and receiver. GPS satellites broadcast signals that allow GPS receivers to calculate their position.In many developed countries,GPS is commonly used as a navigator to guide drivers to a specific location.GPS provides the same precise guidance for field operations.The system allows farmers to reliably identify field locations so that inputs (seeds,fertilizers,pesticides,herbicides and irrigation water) can be applied to an individual field, based on performance criteria and previous input applications (Batte and VanBuren, 1999).Perry (2005) highlights the specific advantages of GPS in farm operations:

- Farm machines are guided along a track hundreds of metres long making only centimetre-scale deviations.

• Rows are not forgotten and overlaps are not made.
• The number of rows can be counted during work.
• Tools and equipment can be operated in the same way from year to year.
• It is possible to work at night or in dirt with precision.
• The system is not affected by wind.
• An additional recorder can store field information to be used in making a map.Sensor technologies various technologies – electromagnetic, conductivity,photo-electricity, and ultrasound – are used to measure humidity, vegetation, temperature, vapour, air etc. Remote-sensing data are used to: distinguish crop species; locate stress conditions; discover pests and weeds;and monitor drought, soil and plant conditions. Sensors enable the collection of immense quantities of data without laboratory analysis. The specific uses of sensor technologies in farm operations are as follows:
• Sense soil characteristics: texture, structure, physical character, humidity, nutrient level and presence of clay (Chen *et al*., 1997).
• Sense colours to understand conditions relating to plant population, water shortage and plant nutrients.
• Monitor yield: crop yield and crop humidity.
• Variable-rate system: to monitor the migration of fertilizers and discover weed invasion.

Geographic information system (GIS)

The use of GIS began in 1960. This system comprises hardware, software and procedures designed to support the compilation, storage, retrieval and analysis of feature attributes and location data to produce maps.GIS links information in one place so that it can be extrapolated when needed. Computerized GIS maps are different from conventional maps and contain various layers of information (e.g. yield, soil survey maps, rainfall, crops, soil nutrient levels and pests). GIS helps convert digital information to a form that can be recognized and used.

Digital images are analysed to produce a digital information map of the land use and vegetation cover. GIS is a kind of computerized map, but its real role is using statistics and spatial methods to analyse characters and geography. Further information is extrapolated from the analysis (ESRI, 2002).A farming GIS database can provide information on: filed topography, soil types, surface drainage, subsurface drainage, soil testing, irrigation, chemical application rates and crop yield. Once analysed, this information is used to understand the relationships between the various elements affecting a crop on a specific site (Trimble, 2005).

Variable-rate technologies (VRT)

Variable-rate technologies (VRT) are automatic and may be applied to numerous farming operations.VRT systems set the rate of delivery of farm inputs depending on the soil type noted in a soil map. Information extrapolated from the GIS can control processes, such as seeding, fertilizer and pesticide application, and herbicide selection and application, at a variable (appropriate) rate in the right place at the right time (Batte and VanBuren, 1999; NESPAL, 2005). VRT is perhaps the most widely used PFS technology in the United States (National Research

Council, 1997).Grain yield monitors for mapping A monitor mounted on a combine continuously measures and records the flow of grain in the grain elevator. When linked with a GPS receiver, yield monitors can provide data for a yield map that helps farmers to determine the sound management of inputs, such as fertilizer, lime, seed, pesticides, tillage and irrigation (Davis, Massey and Massey, 2005).

Crop management

The precision farming system employs the innovations and technologies described above (Rickman *et al*., 1999).Thanks to satellite data, farmers have a better understanding of the variation in soil conditions and topography that

influence crop performance within the field. Farmers can, therefore, precisely manage production factors, such as seeds, fertilizers, pesticides, herbicides and water control, to increase yield and efficiency. In the United States, for example, the management scheme of typical PFS comprises the following practical steps (NESPAL, 2005):
1. Determine management zones to be applied with PFS.
2. Establish yield goals.
3. Carry out soil sampling and data interpretation.
4. Make decisions regarding management of land preparation, varieties, fertilizers and other nutrients to achieve yield goals.
5. Establish maps to discover the pest population: insects, diseases and weeds, using an integrated pest management (IPM) approach.
6. Apply precision irrigation.
7. Apply logging and automated record keeping.
8. Monitor and establish yield maps, evaluate PFS response and identify strengths and weaknesses for future improvement.

The Australian Centre for Precision Agriculture (2005) is currently focusing on the application of PFS in crop production and its site-specific crop management includes five main processes:
1. Spatial referencing. Collecting data on the spatial variation in soil and crop features requires accurate position determination in the field, using GPS.
2. Differential action. In response to spatial variability, farming operations, such as sowing rate, fertilizer, pesticide and lime application, tillage and water use, can be varied in real time across a field. Variation in treatment corresponds to the mapped variation in the field attributes measured.
3. Soil and crop monitoring. Soil and crop attributes are monitored on a finite scale. When observations are targeted with GPS, they provide data on the spatial variability of the attributes within a field.
4. Spatial prediction and mapping. Values for soil and crop attributes are predicted for ensample locations across a field. This enables detailed representation of the spatial variability within an entire field through the creation of a smoothed map.
5. Decision support. Knowledge about the effects of field variability on crop growth – and the suitable agronomic responses – can then be combined to formulate differential treatment strategies.

Basic Steps in Precision Farming

The basic steps in precision farming are,
i). Assessing variation

ii). Managing variation and
iii). Evaluation

i). Assessing variability

Assessing variability is the critical first step in precision farming. Since it is clear that one cannot manage what one does not know. Factors and the processes that regulate or control the crop performance in terms of yield vary in space and time. Quantifying the variability of these factors and processes and determining when and where different combinations are responsible for the spatial and temporal variation in crop yield is the challenge for precision agriculture.

Techniques for assessing spatial variability are readily available and have been applied extensively in precision agriculture. The major part of precision agriculture lies in assessing to spatial variability. Techniques for assessing temporal variability also exist but the simultaneous reporting a spatial and temporal variation is rare. We need both the spatial and temporal statistics. We can observe the variability in yield of a crop in space but we development over the growing season, which is nothing but the temporal variation. Hence, we need both the space and time statistics to apply the precision farming techniques. But this is not common to all the variability/factor that dictate crop yield. Some variables are more produced in space rather with time, making them more conducive to current forms of precision management.

ii). Managing variability

Once variation is adequately assessed, farmers must match agronomic inputs to known conditions employing management recommendations. Those are site specific and use accurate applications control equipment. We can use the technology most effectively. In site-specific variability management.

We can use GPS instrument, so that the site specificity is pronounced and management will be easy and economical. While taking the soil/plant samples, we have to note the sample site coordinates and further we can use the same for management. This results in effective use of inputs and avoids any wastage and this is what we are looking for.

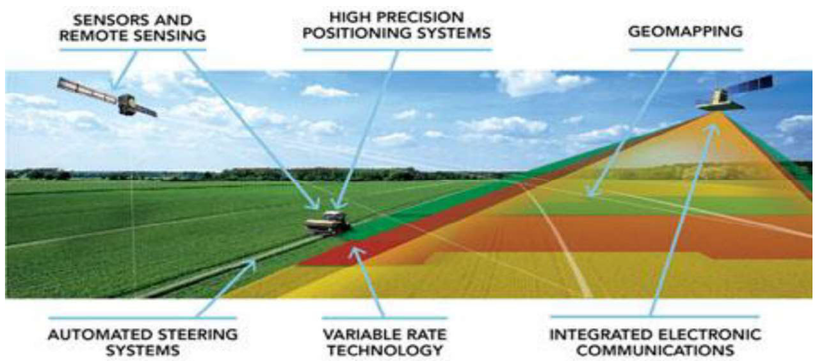
The potential for improved precision in soil fertility management combined with increased precision in application control make precise soil fertility management as attractive, but largely unproven alternative to uniform field management. For successful implementation, the concept of precision soil fertility management requires that within-field variability exists and is accurately identified and reliably interpreted, that variability influences crop yield, crop quality and for the environment. Therefore inputs can be applied accurately. The higher the spatial dependence of a manageable soil property, the higher the potential for precision management and the greater its potential value. The degree of difficulty, however, increases as the temporal component of spatial variability increases. Applying this hypothesis to soil fertility would support that Phosphorus and Potassium fertility are very conducive to precision management because temporal variability is low. For N, the temporal component of variability can be larger than its spatial component, making precision N management much more difficult in some cases.

iii). Evaluation

The most important fact regarding the analysis of profitability of precision agriculture is that the value comes from the application of the data and not from the use of the technology Potential improvements in environmental quality is often cited as a reason for using precision agriculture. Reduced agrochemical use, higher nutrient use efficiencies, increased efficiency of managed inputs and increased production of soils from degradation are frequently cited as potential benefits to the environment. Enabling technologies can make precision agriculture feasible, agronomic principles and decision rules can make it applicable and enhanced production efficiency or other forms of value can make it profitable.

The term technology transfer could imply that precision agriculture occurs when individuals or firms simply acquire and use the enabling technologies. While precision agriculture does involve the application of enabling technologies and agronomic principles to manage spatial and temporal variability, the key term is manage. Much of the attention in what is called technology transfer has focused on how to communicate with the farmer. These issues associated with the managerial capability of the operator, the spatial distribution of infrastructure and the compatibility of technology to individual farms will change radically as precision agriculture continues to develop (Pierce and Peter, 1999).

Precision Farming: key technologies



The concept of precision agriculture first emerged in the United States in the early 1980s. In 1985, researchers at the University of Minnesota varied lime inputs in crop fields. It was also at this time that the practice of grid sampling appeared (applying a fixed grid of one sample per hectare). Towards the end of the 1980s, this technique was used to derive the first input recommendation maps for fertilizers and pH corrections. The use of yield sensors developed from new technologies, combined with the advent of GPS receivers, has been gaining ground ever since. Today, such systems cover several million hectares.
In the American Midwest (US), it is associated not with sustainable agriculture but with mainstream farmers who are trying to maximize profits by spending money only in areas that require fertilizer. This practice allows the farmer to vary the rate of fertilizer across the field according to the need identified by GPS guided Grid or Zone Sampling. Fertilizer that would have been spread in areas that don't need it can be placed in areas that do, thereby optimizing its use.

Key Technology

High precision positioning systems (like GPS) are the key technology to achieve accuracy when driving in the field, providing navigation and positioning capability anywhere on earth, anytime under any all conditions. The systems record the position of the field using geographic coordinates (latitude and longitude) and locate and navigate agricultural vehicles within a field with 2cm accuracy.

Automated steering systems: enable to take over specific driving tasks like auto-steering, overhead turning, following field edges and overlapping of rows. These technologies reduce human error and are the key to effective site management:

1. Assisted steering systems show drivers the way to follow in the field with the help of satellite navigation systems such as GPS. This allows more accurate driving but the farmer still needs to steer the wheel.
2. Automated steering systems, take full control of the steering wheel allowing the driver to take the hands off the wheel during trips down the row and the ability to keep an eye on the planter, sprayer or other equipment.
3. Intelligent guidance systems provide different steering patterns (guidance patterns) depending on the shape of the field and can be used in combination with above systems.

Geomapping: used to produce maps including soil type, nutrients levels etc in layers and assign that information to the particular field location.

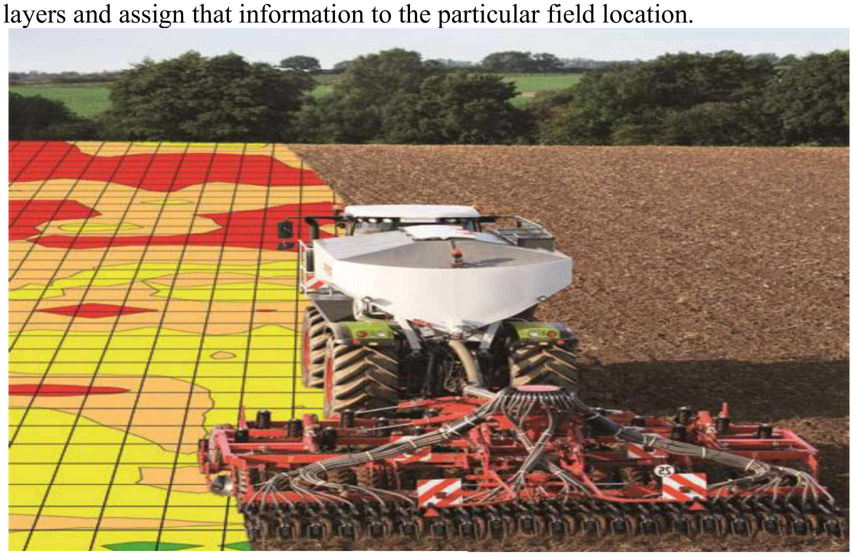


Figure2 Seeder using a geomapping system

Variable rate technology (VRT): ability to adapt parameters on a machine to apply, for instance, seed or fertiliser according to the exact variations in plant growth, or soil nutrients and type.

Sensors and remote sensing: collect data from a distance to evaluating soil and crop health (moisture, nutrients, compaction, and crop diseases). Data sensors can be mounted on moving machines.

Integrated electronic communications between components in a system for example, between tractor and farm office, tractor and dealer or spray can and sprayer.

Precision Farming and Tools of Precision Farming

Precision Farming

Precision Farming is generally defined as information and technology based farm management system to identify, analyze and manage variability within fields for optimum profitability, sustainability and protection of land resources. Precision Farming is helping many farmers worldwide to maximize the effectiveness of the crop inputs including seed quality, fertilizers, pesticides and irrigation water (Pathak, 2003). However, the conventional definition of Precision Farming is most suitable when the land holdings are large and enough variability exists between the fields. In India, the average land holdings are very small, even with large and progressive farmers. The more suitable definition for Precision Farming in the context of Indian farming scenario could be- precise application of agricultural inputs based on soil, weather and crop requirement to maximize sustainable productivity, quality and profitability. Today, because of increasing input costs and decreasing commodity prices, the farmers are looking for new ways to increase efficiency and reduce costs. In this regard, Precision Farming is an alternative to improve profitability and productivity.

Tools of Precession Farming

Precision Farming is a combination of application of different technologies. All these combinations are mutually inter related and responsible for developments. The same are discussed below:

Global Positioning System (GPS): It is a set of 24 satellites in the Earth orbit. It sends out radio signals that can be processed by a ground receiver to determine the geographic position on earth. It has a 95% probability that the given position on the earth will be within 10-15 meters of the actual position.

Geographic Information System (GIS): It is software that imports, exports and processes spatially and temporally geographically distributed data.

Grid Sampling: It is a method of breaking a field into grids of about 0.5-5 hectares. Sampling soil within the grids is useful to determine the appropriate rate of application of fertilizers. Several samples are taken from each grid, mixed and sent to the laboratory for analysis.

Variable Rate Technology (VRT): The existing field machinery with added Electronic Control Unit (ECU) and onboard GPS can fulfill the variable rate requirement of input. Spray booms, the Spinning disc applicator with ECU and GPS have been used effectively for patch spraying. During the creation of nutrient requirement map for VRT, profit maximizing fertilizer rate should be considered more rather than yield maximizing fertilizer rate.

Yield Maps: Yield maps are produced by processing data from adapted combine harvester that is equipped with a GPS, i.e. integrated with a yield recording system. Yield mapping involves the recording of the grain flow through the combine harvester, while recording the actual location in the field at the same time.

Remote Sensors: These are generally categories of aerial or satellite sensors. They can indicate variations in the colours of the field that corresponds to changes in soil type, crop development, field boundaries, roads, water, etc. Arial and satellite imagery can be processed to provide vegetative indices, which reflect the health of the plant.

Proximate Sensors: These sensors can be used to measure soil parameters (N and pH) and crop properties as the sensor attached tractor passes over the field.
Computer Hardware and Software: In order to analyze the data collected by other Precision Agriculture technology components and to make it available in usable formats such as maps, graphs, charts or reports, computer support is essential along with specific software support.

Scope and Limitation in Adoption of Precision Farming in India

Precision Farming concepts are applicable to all agricultural sectors like animal farming, fisheries and forestry. Precision Agriculture (PA) can be classified into two categories namely 'Soft' PA and 'Hard' PA. 'Soft' Precision Agriculture mainly depends on visual observation of crop and soil and management decision based on experience and intuition, rather than statistical and scientific analysis. Whereas, 'Hard' PA utilizes all modern technologies like GPS, GIS, VRT, etc. In India 96 million farms out of a total 105.3 million farms have less than 4 hectares (ha) area. Though only fragmented lands are cultivated, the present food grain production in India is nearly 200 Million Tone, which has made India self sufficient in food production. To compete with the world production, the crop yield per hectare must be economic and without environment degradation. In India, overall fertilizer consumption rate is 84.3 Kg/ha, which must be reduced by systematic soil testing and creating nutrient maps along with fertilizer recommendations (Lal, 2004). Along with nutrient zones pest control, disease and weed management also plays an important role in high yield of crop. Using advance technology, it is possible to monitor and control the pest and disease at lower costs. Some states like Punjab, Haryana use high doses of fertilizer and pesticides. For example, the state of Punjab has 1.5% of total geographical area of India, but uses 1.38 million tones (nearly 10% of all India fertilizer consumption) of NPK fertilizer along with 60% of weedicides used in India. Overall exploitation of land as well as excessive use of agriculture input are typical problems of these areas.

Stress management is another area where Precision Framing can help Indian farmers in scheduling irrigation more profitably by varying the timing, quantity and placement of water. Mechanization of farming helps the farmers to reduce the labor cost and to improve the accuracy of farming including quality seed selection, weed removing, pesticide and fertilizer application, harvesting and sorting of the crop as per the quality.

There are many limitations to adoption of Precision Farming in developing countries in general and India in particular. Some of these limitations are common to those in other regions; however, following are specific to Indian conditions:

1. The culture and perceptions of the users,
2. Small farm size,
3. Lack of success stories,
4. Heterogeneity of cropping systems and market imperfections,
5. Land ownership, infrastructure and institutional constraints,
6. Lack of local technical expertise
7. Availability, quality and cost of data.

1.4 Need of Precision Farming in Sugarcane Agriculture

India is world's second largest producer of sugar and sugarcane. Sugarcane is cultivated in about 4.09 million hectares, producing about 283 million tones of cane with an average productivity 69.19 MT/ha. Of the several agriculture crops, sugarcane is the most remunerative, its requirements for water and fertilizer are also equally very high. About 60% of cane in India is in the Subtropical Zone and 40% in the Tropical Zone. The productivity is 89 MT/ha in sub tropical zone and 58 MT/ha in tropical zone. The productivity in Madhya Pradesh is lowest, 39.3 Mt/ha and that of Tamilnadu is highest, 134.2 MT/ha in the country. The productivity of sugarcane is declining due to following reasons:

1. Non availability of high yielding varieties,

2. Dearth of good quality seed,
3. Improper water management,
4. Use of imbalanced doses of fertilizers,
5. Negligence in plant protection,
6. Low awareness among the farmers to use improved cultivation practices,
7. Poor attention to Raton crops.

Precision Agriculture

The systematic implementation of best management practices into a site-specific system provides the best opportunity to develop a truly sustainable agriculture system. Managing the right source at the right rate, right time and in the right place is best accomplished with the right tools. Various technologies are available to help make decisions related to nutrient management, from soil sampling to fertilizer application to yield measurement. These tools enhance the ability to fine-tune nutrient management decisions and develop the site-specific nutrient management plan for each field.

Identify and Quantify Variability within Fields

Variability within fields is measured by soil sampling, field scouting, physical measurements, soil survey, and yield monitoring. Documenting this information in the GIS database for a field provides the basis for site-specific management decisions. Variability within fields comes from a variety of natural and man-made factors. Natural variability is largely due to physical properties of the soil including topography, texture and structure. Man-made influences on soil variability include:

1. Crop rotation, livestock pasture, fences, tile drainage, fertilizer and manure application;
2. Cropping systems and tillage operations affect soil tilth; and
3. Compaction (a result of a combination of natural and man-made factors).

Site-Specific Equipment and Technology

Equipment

Special equipment is not required for site-specific management. Identifying areas requiring specific management can be done with conventional soil testing and scouting techniques. Different fertilizer rates can be applied to different areas by staking or flagging them, and then spreading the different areas separately. Estimates of within-field distances to identify these areas can be documented by measuring, counting rows, pacing or other relative means. But there are technology tools available that expand the capabilities for using site-specific management more effectively.

Technology Tools

GPS, GIS-based records and data analysis, sensors and variable-rate controllers are revolutionizing nutrient management to best meet crop needs and efficiently utilize available resources. Site-specific sampling, variable-rate fertilizer application and yield monitors are among the most common tools guiding today's modern nutrient management systems.

Global Positioning System (GPS)

Most of the tools for precision agriculture involve use of data collection or controller systems that utilize the global positioning system (GPS). Each set of data collected is associated with its specific geographic coordinates (latitude, longitude, and elevation). This allows the understanding of precise relationships among the different layers of data, the resulting yield data, and other measurements. These layers can then be analyzed to make recommendations for future decisions.

GPS systems are used on planting equipment for collecting geo-referenced planting data, starter fertilizer application, and other inputs. With proper controllers, variable-rate application of inputs can be added to the management plan. Each of these steps can be added over time, increasing the value of the initial investment.

As more advanced military-technology becomes available for public use and new technologies develop to support GPS, this tool will continue to become more valuable to farmers in implementing site-specific management.

Real-Time Kinematic System (RTK)

GPS is used at different levels of precision, depending on the application and availability of information. The most precise system currently used in crop production applications is the Real-Time Kinematic (RTK) system.

The high-accuracy RTK guidance systems help avoid costly skips and overlaps, saving on input costs for seed, fertilizer and pesticides. Reduced operator stress and fatigue are major added benefits. RTK systems use a base station that transmits its location to the rover GPS receiver (on the implement), which is used to correct the position of the roving unit to the position of the known fixed base station. Such systems typically provide accuracy within 1 or 2 cm in position and from year to year. This enables accurate row-to-row positioning, eliminates skips and improves accuracy of harvest monitoring data. RTK is also used to provide similar accuracy for multiple passes, such as banding starter fertilizer in the fall matched with seeding in the spring.

Geographic Information System (GIS)

Geographic Information Systems (GIS) consist of data and software designed for spatial analysis of GPS-referenced data. Various databases in an agricultural GIS system might include soil survey data, soil test information, pest infestations, yield data, remote sensing imagery and other types of observations and records that can be collected and referenced with their geographic position (by GPS). These data sets can then be converted to maps to illustrate their spatial variability within the field and become additional layers in the field database.

The capability of GIS is more than mapping. The real power of GIS software lies in calculations and analysis of the georeferenced data sets to correlate their effects on yields and interactions with other production factors. By using models integrating the different spatially-variable data sets, responses to inputs can be predicted, or interactions affecting yield can be identified. Accumulated over time, the GIS data sets become increasingly useful as record-keeping and prediction tools.

Soil Surveys

For site-specific management, it is important to understand the variability in soil characteristics, which can be done through soil surveys. The Web Soil Survey provides over 2300 geographically-referenced digital soil surveys for free download from the USDA Natural Resources Conservation Service (NRCS) website. This information helps relate soil characteristics to site-specific variability observed in crop yield.

Intensive Soil Sampling

Site-specific production systems will usually require more intensive soil sampling. The most common is a 2 to 3 acre grid, preferably taken on a systematic, unaligned grid basis. (See soil sampling chapter.) Research has shown an advantage to shifting to a 1-acre grid, or even smaller where the field is known to be highly variable. GPS-equipped sampling systems document the precise location of the samples, so the test results can be used to guide nutrient decisions and to facilitate correlation with yield maps, soil survey, and other datasets. Now subsequent samples, fertilizer and manure applications, and crop removal can all be analyzed as additional layers in the GIS database for the field, and used for calculating such details as fertilizer recommendations, nutrient use efficiency, and selected environmental parameters.

Remote Sensing

Remote sensing is becoming a useful tool for precision farming, using scanners on aircraft or satellites to monitor changes in wavelengths of light from fields and growing crops. Satellite imagery is also useful in more precise mapping of field boundaries and location of tile drainage lines, for example, and is often most effective when used in conjunction with field scouting ("ground truth observations") to help identify the reasons for variability. The data collected can be mapped and analyzed with the help of GIS tools, to provide additional data layers for GIS analysis and management decisions.

Remote sensing helps to define the extent of problems identified in field scouting by recognizing similar patterns. It is used to document such issues as pest problems, weather factors, nutrient management issues, and more. While it has taken several years to develop remote sensing technology to the point of providing dependable, cost effective products and services in a timely fashion, there are now such services available to add to the toolbox to aid farmers and their advisors in making crop management decisions.

Emerging technologies

Precision agriculture is an application of breakthrough digital farming technologies. Over $4.6 billion has been invested in agriculture tech companies—sometimes called agtech.[7]

Robots

Self-steering tractors have existed for some time now, as John Deere equipment works like a plane on autopilot. The tractor does most of the work, with the farmer stepping in for emergencies. Technology is advancing towards driverless machinery programmed by GPS to spread fertilizer or plow land. Other innovations include a solar powered machine that identifies weeds and precisely kills them with a dose of herbicide or lasers. Agricultural robots, also known as AgBots, already exist, but advanced harvesting robots are being developed to identify ripe fruits, adjust to their shape and size, and carefully pluck them from branches (Plant et al., 2000)

Drones and satellite imagery

Advances in drone and satellite technology benefits precision farming because drones take high quality images, while satellites capture the bigger picture. Light aircraft pilots can combine aerial photography with data from satellite records to predict future yields based on the current level of field biomass. Aggregated images can create contour maps to track where water flows, determine variable-rate seeding, and create yield maps of areas that were more or less productive.

The Internet of things is the network of physical objects outfitted with electronics that enable data collection and aggregation. IoT comes into play with the development of sensors and farm-management software. For example, farmers can spectroscopically measure nitrogen, phosphorus, and potassium in liquid manure, which is notoriously inconsistent.They can then scan the ground to see where cows have already urinated and apply fertilizer to only the spots that need it. This cuts fertilizer use by up to 30% (Pedersen et al., (2004). Moisture sensors in the soil determine the best times to remotely water plants. The irrigation systems can be programmed to switch which side of tree trunk they water based on the plant's need and rainfall.

Innovations are not just limited to plants—they can be used for the welfare of animals. Cattle can be outfitted with internal sensors to keep track of stomach acidity and digestive problems. External sensors track movement patterns to determine the cow's health and fitness, sense physical injuries, and identify the optimal times for breeding. All this data from sensors can be aggregated and analyzed to detect trends and patterns.

Misconceptions about Precision Agriculture

There are several mistaken preconceptions about precision agriculture.

a). Precision agriculture is a cropping rather than an agricultural concept

This is due to cropping systems, in particular broad-acre cropping, being the face and driving force of PA technology. However precision farming concepts are applicable to all agricultural sectors from animals to fisheries to forestry. In fact it might be argued that precision farming concepts are more advanced in the dairy industry where the “site” becomes an individual animal, which is recorded, traced and fed individually to optimize production.

These industries are just as concerned with improved productivity and quality decreased environmental impact and better risk management as the cropping industry however precision farming concepts have yet to be applied on the same scale in these areas. For example a grazer's use of advance warning meteorological data and market predictions to estimate fodder reserves and plan livestock numbers is a form of precision farming.

b). Precision agriculture in cropping equals yield mapping

Yield mapping is a crucial step and the wealth of information farmers are able to obtain from a yield map makes them very valuable. However they are only a stepping-stone in a precision farming management system. The bigger agronomic hurdle lies in retrieving the information in the yield map and using it to improve the production system. The advance of PA adoption (usefulness) in this country is may soon be bottlenecked at this point due to the lack of decision support systems (DSS) to help agronomists and farmers understand their yield maps. Yield maps may not tell the whole story either with other data sources, e.g.crop quality and soil maps, economic indicators or weather predictions, proving further information necessary for correct agronomic interpretations.

c). Precision agriculture equals sustainable agriculture

Precision agriculture is a tool to make agriculture more sustainable however it is not the total answer. Precision farming aims at maximum production efficiency with minimum environmental impact. Currently it is the potential for improved productivity (and profitability) that is driving precision farming rather than the more serious issue of long-term sustainability. Precision farming will not fix problems such as erosion and salinity by itself although it will help to reduce the risk of these problems occurring. Sensible sustainable practices still need to be used in conjunction with precision farming.

Obstacles

There are many obstacles to adoption of precision farming in developing countries in general and India in particular. Some are common to those in other regions but the others are specific to Indian conditions are as follows. (1) Culture and perceptions of the users (2) Small farm size (3) Lack of success stories (4) Heterogeneity of cropping systems and market imperfections (5) Land ownership, infrastructure and institutional constraintsand (6) Lack of local technical expertise

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