**Drip irrigation: Where Every Drop Count**

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**1.1 Introduction**

Irrigation is the artificial application of water needed to the crop. It is the single most important input in agriculture. It is said that green revolution in India was possible largely due to availability of irrigation water. The agricultural production particularly the cereals have increased over the years almost in proportional to irrigation facility created and utilized. Over the last twelve five year plans during 1950-51 to 2017-18 the irrigation potential has been increased at the rate of about 342.30% (CWC, 2017& Jain *et al.,*2019) against the production of cereals about 500%(Acharya,2010 &Anonymous1).The groundwater has contributed about 60% (Gandhi & Vaibhav, 2011) of increased irrigation potential by the enormous number of tube well in irrigated area(Gandhi & Vaibhav, 2011). Groundwater in some area is the readily available water and the farmers prefer to use it as because the source of water in most of the casesis in their field and at the same time gets the opportunity of absolute command on the use of it. This opportunity has led to overexploitation of groundwater. The farmers are in general habituated to cultivate the crops of good return without much consideration to amount of water use or even not much concerned to minimization of water losses in their irrigation system. In India, about two-third of the water is diverted from the source gets lost in conveyance or otherwise under the surface irrigation system (Biswas, 2014). Overexploitation of the groundwater reported to be the cause of arsenic, lead, fluoride, etc.,heavy metal in irrigation water and so in our food chain.

Irrigation water has become more and precious. Now a day the popular slogan is ‘every drop more crop’. Agriculture sector alone uses about 80% of our usable water resources. The judicious use of irrigation water may save use us from thwart of agricultural production as well as may provide the scope to meet up the increasing demand from the domestic and industrial sectors. The need of irrigation water may be checked or reduced by selecting the alternative low water requiring crops where agro-climatic condition and general food habit of the people permits and/ or adopting good method and practice of application of irrigation water along with efficient soil-crop-water management.

Micro irrigation technologies mainly drip and sprinkler irrigation methods are the solution that reduces conveyance and distribution losses and allows higher water use efficiency. Minimizing water use also reduces energy use for pumping groundwater. There has been a tremendous growth in the area under micro irrigation during the last 15 years. In India, area under micro-irrigation is only 7.73Mha at present. Out of this, drip and sprinkler irrigation coverage is 3.37&4.36Mha respectively, whereas its theoretical potential is estimated at around 69.00Mha, and untapped potential is 61.80Mha. But in West Bengal only 150.00ha area is practiced under the micro irrigation in 2011(Palanisami *et al*., 2011). It may be presumed that there is not much change in micro irrigation practice over the years due to different reasons though Govt. departments are trying to popularize it. Improving water use efficiency (WUE) in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water used by plant) and reduction in water losses from the crop root zone. Improving water use efficiency by 40% on rain fed and irrigated lands would be required to counterbalance the need for additional withdrawals for irrigation over the next 25 years to meet the additional demand for food. Growing more crops per drop of water use is the key to mitigate the water crisis, and this is a big challenge to many countries (Pal *et al.,* 2013).

Among the irrigation system, drip irrigation helps in maintaining the optimum soil moisture in soil root zone with increased yield and water use efficiency. Efficient use of water is highly critical to sustain agricultural production, more particularly in the context of declining per capita land and water availability. Drip irrigation is precise irrigation technology and it gives an opportunity to meet crop water requirements in an optimum way. Analysis of the hydraulics of drip irrigation system is necessary in order to study the dynamics of wetting front advance in the soil and the crop root zone. In India the work on hydraulics of surface and subsurface drip irrigation has been conducted at some places but those results vary depending upon the type of the soil. A quantitative understanding of soil water distribution during drip irrigation is essential to enhance the crop production and water use efficiency by minimizing deep percolation and evaporation losses. Drip irrigation facilitates avoiding stress of water but simultaneously provides an optimal aeration in the soil thereby increasing yield and saving water. Work on drip irrigation for wide row crops like vegetable, cotton, sugarcane, *arhar* and maize has already been done but there is no recommendation of drip irrigation for narrow row crops like rice, wheat etc.

Drip irrigation is an efficient method of application of water at the plant bottom at a rate nearly equal to the consumptive use rate of the plant, thereby minimizing the conventional water losses like percolation, runoff and evaporation from soil. It is a process of slow application of water on, above or beneath the soil by the surface, sub-surface, bubbler, and spray or pulse system. Fertilizer can also be applied with the drip water. Emitters or applicators are placed closed to the plants and used to spray water in the form of drops, tiny streams or miniature spray. In the drip system water applied from the point source advances in all direction in the soil outward from the source. Drip irrigation is essentially a low rate, low pressure, frequent and long duration application of water in plants root zone area.

Drip irrigation is also called as localized irrigation, trickle irrigation, daily flow irrigation, diurnal irrigation, drop irrigation, sip irrigation, and micro-irrigation. A particular name is being popularized in any area depending on the choice of the people of that area. The International Commission for Irrigation and Drainage (ICID) has recommended the term micro-irrigation while the American Society of Agricultural Engineers (ASAE) has preferred drip irrigation. In India it is told as drip irrigation.

**1.2 Histories**

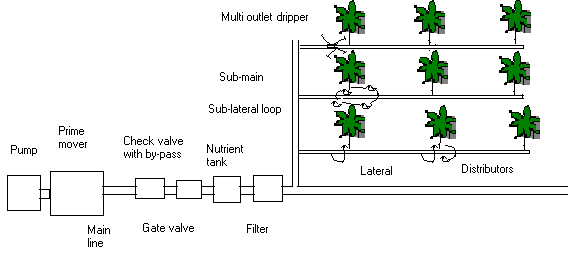
Early in the 1940s, an Israeli engineer named Symcha Blass noticed that a large tree close to a leaking tap was growing more than other nearby trees, despite not receiving more water from the tap. He developed the idea of an irrigation system as a result of this observation, which would use extremely little water, literally drop by drop. A low-pressure irrigation system was eventually created and patented by him. After World War II, plastic pipes were widely used, which led to the development of drip irrigation in Denmark. Later, England embraced the practise. Israeli desert regions of the Negev and Arava demonstrated remarkable success with drip irrigation in the early 1960s. After being presented in the USA, it was quickly and widely accepted.

In India, drip irrigation was carried out using traditional techniques like pitcher/porous cup irrigation, perforated clay pipes, and bamboo pipes. The Meghalayan tribal farmers utilise long hollow bamboo pipes with varied diameters (50-100 cm) to construct channels for drip irrigation of their betel, pepper, and areca nut crops. The water comes from hill streams that are channeled to hill slopes; the head discharge rate ranges from 10 to 30 litres per minute and is decreased to 10 to 30 droplets per minute when the water is applied.The method for utilising them involves planting 500ml-capacity earthen containers along the side of the plant.

The National Seminar held in 1987 by NCPA discussed the system's effectiveness and future promotion strategy. The IPCL's sufficient technical and raw material support prompted business owners to set up drip manufacturing facilities. They provided the farmers with a wide range of pre- and post-sale services, which had a significant impact on growing the drip area. By including farmers and other organisations such as banks, volunteer organisations, universities, government agricultural departments, and NABARD in the development process, IPCL and the integrated strategy of NCPA were able to assist PDCs across the nation.

**1.3 Components of Drip Irrigation System**

The basic essential components of a drip system consist of a pump, distribution lines (main, sub-main, and laterals) and drippers. For better control and monitoring the irrigation, the system also includes the equipments, viz. valves, pressure regulators, filters, pressure gauzes, fertilizer applicator, etc.**(Fig.1).**



**Fig. 1** Basic components of a drip irrigation system(Source: Biswas, 2015)

**Pump and prime mover:** In order to supply water through the system's components at a specific amount of pressure, a pump with the necessary capacity is employed. The water comes from a tank most of the time. On the other hand, drip irrigation can also be employed with groundwater directly. There is a chance that the water may contain organic and inorganic foreign things if the source of supply is a farm pond or natural stream. Suction filters should be utilised in this situation to get relatively pure water. The typical primary mover of the pump is either an electric motor or a diesel engine. Recently, efforts have been made to increase the popularity of the solar pump for drip irrigation. Although piston pumps can be utilised in small systems, centrifugal pumps are more frequently

**Control head:** The control head of the drip system is responsible to regulate the pressure and water supplied, filtering of water, and addition of nutrients in it. This component includes the fertilizer applicator (tank), filter, and some control valves.

**Fertilizer tank:** Nitrogen, in particular, is added to drip water using a fertiliser tank. As a result, less fertiliser is needed and fertiliser can be applied directly with irrigation water. The tank is a small vessel that is connected to the main line at both its input and outlet. According to the diagram, part of the flow is immediately diverted to the tank to dissolve the nutrients before continuing on to join the main stream through the exit. Sometimes a venturi is used to connect the tank to the main line. As a result, tank water is forced into the main line by increasing the velocity head and developing the suction.

**Filter:** The control head of a drip system installation must to contain a premium filter. The filter is used to filter out any suspended impurities from the water before it gets to the drippers from the pump. Impurities may obstruct the path of drippers and irrigation water's perforations. The success of drippers is significantly influenced by the filter's performance.

**1.4 Distribution lines:**

**Main line:** The main line carries the total amount of water for the irrigation system. It connects the different sub-mains to water source. The main pipes are commonly made of flexible material such as PVC (poly vinyl chloride) or plastics. However, the rigid pipe of asbestos cement or galvanized steel is also used similar to main line for conventional sprinkler irrigation.

**Sub-main:** The sub-main feed to the laterals on one or both sides. It is made of either of medium density polyethylene (PE) or of PVC. There should be balance between the diameter of main and sub-mains. These are determined in consideration to rate of discharge, number of sub-mains, and friction losses in pipes.

**Laterals:** It is more commonly made of low density PE of usual diameter 1 to 1.25cm. The 1.2cm diameter laterals are popularly used. In some exception cases the small diameter rigid PVC pipe laterals are found in use. The distributors are connected to predetermine spacing in the laterals or near the plants in the case of orchards. The individual lateral length is usually limited to 40m and a pressure drop of maximum 10 percent between the two ends of a lateral.

**Distributors:** The distributors drip the water at low discharge rate and at atmospheric pressure. The distributors may be a dripper or a nozzle, a micro tube or any type of commercially manufactured outlet.

**1.5 Types of Drip System**

The following are the types of drip system.

**i. Surface drip**

Emitters and lateral lines are placed on the top layer of the soil in a surface drip system. The most typical and well-liked drip system is this one. Row crops and plants with broad spacing can both use it. For single outlet point-source emitters and line source emitters, the discharges are less than 12 lpm. The benefits of using surface drip are its simple installation and inspection, the ability to change and clean the emitters, the ability to observe the surface wetting pattern, and the ability to measure the discharge rates of individual emitters.

**ii. Sub-surface drip system**

Through the emitters, water is gradually applied below the surface in this system. Sub-surface drip is distinct from sub-irrigation, which irrigates the root zone via regulating the water table. Because the early issues of extensive blockage have been resolved, sub-surface drip systems are now more widely accepted. Emitters directed upward have been proven to operate more effectively. A sub-surface drip system may have a longer operational life while causing minimum disruption to any cultural or agricultural practises. By burying the laterals and setting the emitters on the surface by the riser tubes (sub-laterals), the surface and sub-surface approaches are occasionally both partially used in the same field. Sub-surface drip systems can also be developed by only employing perforated or porous pipes.

**iii. Bubbler**

In bubbler irrigation, water is applied from a single point source in the shape of a small stream or fountain at a discharge rate that is higher than that of surface and subsurface drip irrigation but often lower than 225 lpm. This application rate is higher than the infiltration rate. In order to manage the water distribution around the facility, a basin is needed. Comparing the bubbler system to the surface and sub-surface drip systems, the bubbler system uses less energy, less filtering, and less repair and maintenance.

**iv. Spray**

This device uses a small spray, jet, fog, or mist to provide water to the soil's surface. In the case of a surface, sub-surface, or bubbler, air serves as the medium for the distribution of water rather than soil. It is often applied at a rate of less than 175 lpm and used to irrigate crops with broad spacing around trees. High winds and evaporation loss might damage a spray system. Its benefits include minimum filtration needs and low repair and maintenance costs.

**v. Mechanical move**

By applying water by a travelling drip, spray, drag, or hose-reel drip system to large-scale row crops, this device expands the bubbler concept. However, the attached lateral lines (which have the linear move) are employed to distribute water as a continuous moving stream to each row in a travelling drip system instead of the sprinkler devices. In comparison to a traditional sprinkler system, the uniformity of water application is good and the pressure required is lower in this system. However, because the rate of application is typically higher than the rate of infiltration, precautions must be taken to minimise soil erosion and runoff.

**vi. Pulse**

The pulse drip system uses emitters with a high discharge rate and short application times. This uses an application cycle of five, ten, or fifteen minutes every hour, and the pulse emitter's discharge rate is typically four to ten times higher than that of conventional emitters. The benefit of a pulse drip system is that clogging may be reduced, but a drawback is the need for an automatic controller and a dependable, affordable pulse emitter. Due to the increased number of application cycles, pulse drip systems may also result in inefficient starting and shutdown.

**1.6 Advantage and Disadvantages**

**Advantages**

i. Easier management

ii. Saving in water

iii. Saving in labor

iv. Increase in plant growth and yield

v. Improved fertilizer and other chemical application

vi. Use of saline water

vii. Limited weed growth

viii. Better use of poor soils

ix. Easier control of pests and weeds

x. No soil erosion

## Disadvantages

1. Initial cost is high
2. Technical knowledge is required to design, installation and maintenance
3. Clogging of emitters is a great problem in many areas
4. Assured source of water is required
5. Inadequate customer services for maintenance and supply of spare parts

**1.7 Success story of Drip irrigation system**

Drip irrigation is an efficient method of application of water at the plant bottom at a rate nearly equal to the consumptive use rate of the plant, thereby minimizing the conventional water losses like percolation, runoff and evaporation from soil. It is a process of slow application of water on, above or beneath the soil by the surface, sub-surface, bubbler, and spray or pulse system. Fertilizer can also be applied with the drip water. Emitters or applicators are placed closed to the plants and used to spray water in the form of drops, tiny streams or miniature spray. In the drip system water applied from the point source advances in all direction in the soil outward from the source. Drip irrigation is essentially a low rate, low pressure, frequent and long duration application of water in plants root zone area (Biswas, 2015).

Drip irrigation is the most energy and water efficient of all the irrigation systems. Water savings of up to 50% compared to sprinkler irrigation are common (Lamont *et al.*2002). Ideally, water is applied in the proper amount to the root ball of the plant, minimizing water leaching from the root zone and minimizing evaporation of water since the water isn’t sprayed into the air (Shock, 2006; Lamont *et al.*2002; Haman and Smajstria, 2010; Schultheis, 2005). The water can be emitted at uniform distances along a pipe or a tube with an emitter that directs water to one plant volume of soil.

During the early 1940's Symcha Blass, an engineer from Israel, observed that a big tree near a leaking tap exhibited more vigorous growth than other trees in the area. This led him to the concept of an irrigation system that would apply water in small quantity literally drop by drop. The earliest drip irrigation system consisted of plastic capillary tubes of small diameter (1.0mm) attached to 1arge pipes. One of the refinements made by Blass in his original system was coiled emitter. In his early 1960's, experiments in the Israel reported spectacular results when they applied the Blass system in the desert area of the Negev and Arava. Drip irrigation unit in their current diverse forms were installed widely in U.S.A, Australia, Israel, Mexico and to a lesser extent in Canada, Cyprus, France, Iran, New Zealand, UK, Greece and India. With the increased availability of plastic pipes and development of emitters in Israel, it has since become an important method of irrigation in Australia, Europe, Israel, Japan, Mexico, South Africa and the United States (INCID, 1994).

Drip method of irrigation helps to reduce the over-exploitation of groundwater that partly occurs because of inefficient use of water under surface method of irrigation. Environmental problems associated with the surface method of irrigation like water logging and salinity are also completely absent under drip method of irrigation (Narayanamoorthy, 1997).

Drip method helps in achieving saving in irrigation water, increased water-use efficiency, decreased tillage requirement, higher quality products, increased crop yields and higher fertilizer-use efficiency (Qureshi *et al.*, 2001; Sivanappan, 2002; Namara *et al.,* 2005). Sandhu *et al.* (2019) reported that wheat under drip irrigation with residue retention system showed significant grain yield increase of 23.10% compared to furrow irrigation with no residue.

Bhowmik *et al*. (2018) revealed that water use efficiency and water savings in all drip irrigated treatments recorded significantly higher than the farmers’ method of irrigation. Wheat with drip irrigation at 100% CPE on two days interval resulted in higher grain yield (5825kg/ha) with less water requirement (207.90mm) compared to conventionally irrigated wheat with less grain yield (4485kg/ha ) and high water requirement (300mm).

Tasal and Pawar (2013) found that the treatment of 100% drip fertigation with foliar sprays was found to be more beneficial than conventional method of irrigation and fertilization in respect of increase in yield (25.60%) with 44.50% water saving which brought 0.8 ha more area under irrigation*.*

Rao and Gangwar (2019) revealed that the highest total energy output was 158,496 MJ/ha for wheat with System of Wheat Intensification (SWI) management using drip irrigation. The highest average energy productivity as 0.12kg /MJ for wheat was the same, SWI management with drip irrigation systems. Drip irrigation is considered as an alternative irrigation approach for better water and fertilizer usage efficiency (Assouline, 2002; Hanson & May, 2003; Eid *et al*., 2013).

Drip irrigation (trickle or micro irrigation) is a promising system for economizing on the available irrigation water. It is also necessary to manage the available water efficiently for maximum crop production. Drip irrigation can supply water both precisely and uniformly at a high irrigation frequency compared to furrow and sprinkler irrigation, thus potentially increasing yield, reducing subsurface drainage, providing better salinity control and better disease management since only the soil is wetted whereas the leaf surface stays dry (Hanson & May, 2007).

A major advantage of drip irrigation systems is the close balance between applied water and crop evapotranspiration that reduces surface runoff and deep percolation to a minimum .For perfect drip irrigation system design, about 40% of the irrigation water is saved with an application efficiency of 85%-95% as compared with other irrigation systems. Trickle systems produce higher ratio of yield per unit area and yield per unit volume of water than typical surface or sprinkler irrigation systems (Ceunca, 1989). Tagar *et al.,* (2012) reported that the drip irrigation method saved 56.40% water and gave 22.00% more yield as compared to that of furrow irrigation method.

Drip irrigation is the modern technique to irrigate the crops. It conveys water only to the crop, decreasing the growth of weeds. The use of drip irrigation is the greatest water-conserving irrigation technique, with slight no wind-blown water and evaporation. Therefore, the study was pointed out many factors that the farmers need to care about them when used drip irrigation system. On the other hand, emitter clogging is considered as a big problem with importance of cost consequences and production. Therefore, technical guidelines for system managements should be adopted and followed. Finally, water is very important and necessary and must be placed in the priorities of our economic plans. So we recommend by using drip irrigation because of its advantages; rationalization in the behavior of water consumption and reducing the loss of water use; training and technical rehabilitation of farmers on the use of modern technologies in irrigation in terms of operation, maintenance and management (Shareef *et al.,* 2019).

In the case of surface irrigation techniques and sprinkler irrigation techniques, the plants are supplied with water to meet its requirements for a long period, sometimes exceeding more than one week. Therefore, that the plants take advantage of it excessively in the first days after irrigation, which leads to reduce in the quantity and quality of the product in addition to the significant loss of water and fertilizer (Sammis,1980).

Labor and operating costs are generally less, and extensive automation is possible. Water applications are precisely targeted. No applications are made between rows or other non-productive areas. Field operations can continue during irrigation because the areas between rows remain dry, resulting in better weed control and lower production costs. Fertilizers can be applied efficiently to roots through the drip system. Watering can be done on varied terrains and in varied soil conditions. Soil erosion and nutrient leaching can be reduced (Marr and Rogers, 1993).

Frequent or daily application of water keeps the salts in the soil water more dilute and leached to the out limits of the wet zone to make the use of saline water more practical (Jensen, 1993). Use of trickle irrigation is practical even in fields that have 5%-6% slope without erosion (Elobeid, 2006). Trickle irrigation needs no leveling, no drainage and no other field operations like ridging.

Raina *et al.*, (1998) reported the water use efficiency was higher under drip irrigation as compared with surface irrigation. Dawood and Hamod (1985) found water use efficiency for trickle irrigated lima beans to be twice as high as that for furrow and sprinkler irrigated lima beans. Sammis (1980) reported higher water use efficiency for trickle and subsurface irrigation as compared to sprinkler and furrow irrigated for potatoes.

Aujla *et al.*, (2007) reported the water use efficiency at 75% which produced the highest fruit yield, was 109.9kg/ha-mm as compared with the 89.9kg/ha-mm in alternate furrow to 73.3kg/ha-mm in each of furrow irrigation.

Yohannes and Tadesse (1998) found that the water use efficiency and irrigation application efficiency values were higher in drip system compared to furrow. Sharmasarkar *et al.,* (2001) reported the water use efficiency and fertilizer use efficiency for drip irrigation were higher than the flood irrigation. Salvin *et al.,* (2000) observed the water use efficiency was considerably higher in drip than basin irrigation. Narayanamoorthy (2003) reported the water use efficiency up to 90% in drip irrigation against the efficiency of 30-40% under furrow method. Shaker (2004) reported the water use efficiency of 4.5kg/m3 for the drip irrigation with 400m3 /fed /month, 2kg/m3 for the surface method and 0.60kg/m3 for the drip with the 800m3 /fed/month. Kode (2000) found field water use efficiency was more than double in drip (578.10kg/ha-cm) than in surface irrigation (233.40kg/ha-cm). Muralikrishnasamy *et al.,* (2006) reported the high water use efficiency was associated with drip irrigation compared with surface irrigation. Bosu *et al*., (1995) reported the maximum water use efficiency through drip irrigation.

Water losses through deep percolation or surface runoff will be reduced, possibly to nearly zero, through drip technology, but more ET will be used by the plant in supporting its reduced plant stress and higher yield. More efficient irrigation systems reduce diversions from streams and increase crop both yield and gross revenue (Peterson, 2005).

Hegde and Srinivas (1991) observed the field water use efficiency was higher under drip (99.90kg/ha/mm) than the (42.70kg/ha/mm) in basin irrigation. Cevik *et al.,* (1988) reported the water use efficiency was also higher in drip irrigation and 50% water saving was observed under drip as compared to basin irrigation. El-Boraie *et al.,* (2009) found the highest value of water use efficiency was obtained by applying the drip irrigation with 100% of ETc distributed every day. Cetin and Bilgel (2002) reported the water use efficiency values were proved to be 4.87, 3.87 and 2.36kg / ha /mm for drip, furrow and sprinkler respectively. Mateos *et al.,* (1991) reported that water use efficiency was 30% larger in the drip irrigation treatments, indicating a definitive advantage of this method under limited water supply.

Malakouti (2004) reported the water use efficiency increased from 5.50kg/m3 in surface irrigation to 8.50kg/m3 for drip irrigation which is an important improvement for irrigated agriculture. Manickasundaram *et al.,* (2002) found the water use efficiency was 20 to 60% higher in drip irrigation treatments compared to that of surface irrigation method treatments compared to that of surface irrigation method. Dagdelen *et al.,* (2009) reported the largest irrigation water use efficiency was observed in the 25% of the soil water depletion under drip (1.46kg/m3 ), and the smallest irrigation water use efficiency was in the 100% treatment (0.81kg/m3 ) the results also demonstrated that irrigation of cotton with drip irrigation method at 75% level had significant benefits in terms of saved irrigation water and large water use efficiency indicating a definitive advantage of deficit irrigation under limited water supply conditions.

Kode (2000) found the total seasonal requirement in drip was 210cm as compared to 402.0cm in surface irrigation treatment indicating 50.50% water saving in drip irrigation. Bashour and Nimah (2004) reported the trickle irrigation saves about 50% of the water used in surface irrigation. Fulton *et al.,* (1991) reported more water was applied with the furrow systems compared to the drip system. Styles *et al.,* (1997) found the furrow system applied 98mm more water compared to the drip system. Manickasundaram *et al.,* (2002) reported the saving in irrigation water under drip scheduled at 50% of surface irrigation was 48.4% compared with that of surface method of irrigation. Hassanli *et al.,* (2009) reported the maximum water saving was obtained using drip irrigation with 5907 m3 /ha water applied and the minimum water saving was obtained using furrow with 6822 m3 /ha. Aujla *et al.,* (2007) reported a saving of 25% water on drip irrigation as compared with furrow irrigation. Francisco *et al.,* (1995) reported the consumptive use of furrow irrigated vines was 12.50% greater than drip irrigated vines.

Some studies were done to compare drip irrigation with surface irrigation. Mohammad *et al.,* (2010) compared different types of irrigation techniques revealed that the drip and sprinkler irrigations methods were more effective and efficient than that of surface irrigation for improved land productivity. Bogle and Hartz (1986) found that furrow and drip irrigation produced similar muskmelon yield and quality; however, rain prior to and during harvest may have masked treatment effects on soluble solids content. Dengiz (2006) concluded that the drip irrigation method increased the land suitability by 38% compared to the surface irrigation method. Also some researchers as cited by Dastane (1980) claimed that more frequent irrigations give higher yield than lesser number of water applications. It was asserted that there is better nutrient uptake and lesser leaching losses at higher every cycle. Liu *et al.,* (2006) reported the drip irrigation was everywhere more suitable than surface irrigation due to the minor environmental impact that it caused. Kuruppuarachchi (1981) has compared banana cultivation under drip irrigation and surface irrigation. It was reported that yield and irrigation efficiency under drip irrigation was 18% and 30%, respectively higher than that of surface irrigation. Thadchayini and Thiruchelvam (2005) reported the 38 highest banana yield 41t/ha in the drip which was 31% higher than from surface irrigation. Srinivas and Hegde (1990) reported that on drip irrigation studies in banana grown on a well drained sandy loam clay loam resulted in a better plant growth, earlier flowering, higher fruit yields and increased water use efficiency compared with basin irrigation. Hegde and Srinivas (1991) reported that there was increase in the banana yield under drip (83.8t/ha) than the basin irrigation (73.5t/ha). Hand bunch and finger weight was also higher in drip. Plants were taller 3% and flowered 15 days earlier under the drip than the basin irrigation. Hegde and Srinivas (1990) reported that there was significant increase in banana yield with drip irrigation (84t/ha) compared to basin system (79t/ha) owing to significant differences in bunch weight mainly due to significant increase in finer weight. Banana plant under drip irrigation flowered 13 days earlier than those under basin irrigation. Cevik *et al.,* (1988) compared drip and basin irrigation system in banana orchards on the South coast of Turkey. The results revealed that yield was higher in drip irrigation compared to basin method.

Kode (2000) conducted an experiment to the effect of water soluble fertilizers applied through drip on growth, yield and quality of banana. The result indicated that the fruit yield was increasing by 16.3% under drip irrigation (84.43kg/ha) compared to surface irrigation (72.61kg/ha). Mahmoud (2006) using three levels of 39 irrigations through drip *viz,* 40%, 60% and 80% of pan evaporation compared with surface irrigation for yield and quality parameters. Irrigation level 40% (674mm per year) in main crop substantially improved growth, bunch, fingers and fruit quality characters with reduction in crop duration and higher available soil nitrogen, phosphorus and potassium. But in ratoon crop, irrigation level of 60% (1187mm per year) was observed to be most economical and effective in getting the best bunch and fingers characters, fruit quality and decreased days to shooting that subsequently reduced the total crop duration, and maintained higher available soil nitrogen, phosphorus and potassium.

Narayanamoorthy (2003) conducted a study on averting water crisis by drip method of irrigation for the water intensive crop and reported the productivity difference between drip and non drip irrigated crops comes to about 27.3t/ha for sugarcane and about 15.3t/ha for banana. That is productivity gain due to the drip method of irrigation is about 25% in sugarcane and 29% in banana.

Salvin *et al.,* (2000) reported the highest bunch weight (14.26kg) and yield 44t/ha were observed under trickle irrigation at 75% evaporation compared to basin irrigation on Cavendish banana cv. Also improved growth, early shooting and higher productivity under drip irrigation.

Raina *et al.,* (1998) found the effect of drip irrigation and plastic mulch as compared to surface irrigation on green pod yield and water use efficiency of pea. They used different irrigation level based on pan evaporation, pan and crop factors. The drip irrigation gave higher yield (9t/ha) as compared to surface irrigation (6t/ha).

Clark (1979) compared the relative efficiencies of drip, sprinkler and furrow irrigation for corn production in Texas. He found water use efficiency of 014, 11.9 and 11.5kg/ha-mm with the three respective systems.

Khalid (1999) compared drip and furrow irrigation system under the same conditions on two varieties of okra. The highest yield was obtained using drip irrigation as compared to furrow irrigation.

Shaker (2004) conducted a study on the effect of drip irrigation system on two varieties of Phaseolus Bean production under the open field condition of Sudan. He used three levels of irrigation water 800m3/fed/month by surface irrigation. 800m3 /fed /month by drip irrigation and 400m3/fed /month by drip irrigation. The highest yield was 492kg/fed, 136kg/fed and 522kg/fed, respectively.

Manickasundaram *et al.,* (2002) evaluated the efficiency of the drip irrigation system in tapioca. The results revealed that scheduling irrigation through drip once in two days at 100%of surface method of irrigation registered the highest mean tuber yield of 58.70t/ha which was significantly superior over surface irrigation scheduled at 0.60 IW/CPE ratios. Howell *et al.* (1989) compared drip and furrow methods for cotton yield. They found that there were no yield differences between drip and furrow irrigation. They also reported that 650mm of irrigation water was needed in order to get a maximum yield. On the other hand, Mateos *et al.,* (1991) obtained 5 and 3t/ha of cotton yield for the drip and furrow irrigation methods, respectively. Yohannes and Tadesse (1998) conducted study to investigate the effect of drip and furrow irrigation on yield of tomato. The higher yield was obtained with drip compared to furrow irrigation. Cetin and Bilgel (2002) reported the effect of three irrigation methods (furrow, sprinkler and drip) on cotton yield. The maximum yield was 4380, 3630 and 3380kg/ha for drip, furrow and sprinkler, respectively. Styles *et al.,* (1997) reported the cotton yield of the drip system was 16% higher than that of the furrow system. Fulton *et al.,* (1991) found the cotton yield was 163kg/ha more for the drip system than for the furrow systems. Tekinel *et al.,* (1989) found that the highest yield was achieved in drip irrigation treatments. However, other methods did achieve similar yield under certain conditions, but with the lower water use efficiency.

Hassanli *et al*. (2009) conducted a study to evaluate the effect of three irrigation methods [subsurface drip (SSD), surface drip (SD) and furrow irrigation (FI)] on yields, water saving and irrigation water use efficiency (IWUE) on corn. The highest yield was obtained with SSD and the lowest was obtained with the FI method.

Tiwari and Singh (2003) used three levels of drip irrigation which applied at 100%, 80% and 60% of the estimated irrigation requirement. The study revealed 62% higher yield in drip as compared to furrow irrigation. The highest yield per unit quantity of water used was 427kg/ha-mm for each of the 60% treatment.

Mustafa and Mohamed (2008) conducted a trial to study the effect of drip irrigation at intervals of one, two and three days compared to surface irrigation every six days on Strawberry. They reported yield 80, 69, 37 and 30 g/plant, respectively. The irrigation every one and two days gave greater vegetative 44 and productive growth. The total amount of water applied under drip irrigation during the two growing seasons was 428mm and 337mm respectively, while it was 1600mm and 1360mm for the surface irrigation for the first and second seasons, respectively.

Aujla *et al. (*2007) reported the effects of different levels of nitrogen (N) and water applied through drip and furrow irrigation on fruit yield of eggplant in the present field investigation, ridge planting with each furrow and alternate furrow irrigation were compared with drip irrigation at three levels of water: 100%, 75% and 50% of each furrow irrigation. The highest yield under drip was obtained under 75% treatment which was 23% higher compared with maximum yield obtained at each furrow irrigation.

**1.8 Drip irrigation in rice cultivation**

Sonit *et al.* (2015) conducted a study on resource management in summer rice through drip irrigationat research farm, IGKV, Raipur, Chhattisgarh and they used drip irrigation system consisting 5 hp pumps with screen filter, 75mm PVC main line, 16mm PVC lateral with dripper distance at 50cm. Water discharge rate 4 l/h was maintained for irrigation. They observed that drip irrigation at 1.4 and 1.2 IW:CPE ratio saved 63 and 59% of irrigation water respectively over flooding, indicating that cropped area under summer rice can be doubled with same quantity of available water by using drip irrigation without sacrificing grain yield.

Bansal *et al.* (2018) conducted an experiment on farm drip irrigation in rice for higher productivity and profitability in Haryana, India and the results revealed that rice grain yield (6950kg/ha) was significantly increased by drip irrigation method compared to flood irrigation (6225kg/ ha ) method.

Rao *et al.* (2017) was carried out at the Central Institute of Agricultural Engineering, Bhopal, India, to evaluate the use of drip irrigation together with modifications in rice crop geometry and other cultural practices. It was found that the system of rice intensification methods adapted with drip irrigation emitters spaced 2.0cm apart gave the highest number of productive tillers at maturity (264.75/m2), also the highest number of grains per panicle (161.75), longest panicle length (27.52.0cm), and highest panicle weight (3.41g).

Drip irrigation maintained a competitive grain yield and water productivity, and greatly reduced pollution risk to the environment. Considering the conservative amount of fertilizer application, less than the amount of fertilization in normal paddy field, the yield potential of rice could be improved by increasing the amount of fertilizer as top application in drip irrigation system (Adekoya *et al.,* 2014).

Sharda*et al.* (2017) found that grain yield 7.34–8.01 and 6.63–7.60t/ ha with 860 and 1455mm water in drip and flood irrigation respectively; water saving by 40–42%; WUE 0.81–0.88 and 0.42–0.52kg/m3 in drip and flood irrigation respectively.

Vanitha *et al.*(2014) evaluated that the Grainyield3.74–4.25t /haindripwith647.50–692.90mmwater i.e. 8–17% higher yield and 7–27% increased water productivity compared to flood; suggested for large root system of rice to be suited for aerobicdrip.Grainyield5.5t/hawith6316m3water(irrigationplusrainfall)in sub-surface dripirrigation(SSDI) compared to 5.5t/hawith 8420 m3water with flood irrigation; water productivity 0.88 and 0.59kg m–3 respectively (Mandal *et al.,*2019).

Soman *et al.* (2018) reported that the rice yields under drip irrigation ranged from 4.50 to 8.20t/ha among the varieties; indicating an increase in yield of 17-22% over from conventional floods irrigation treatment. The water saved in drip method was around 50-61%. Highlighting that drip method of irrigation results in high water use efficiency, it was recorded that the water productivity of rice from 0.365kg/m3 to 0.714kg/m3 among the varieties tested. The water productivity obtained in flood method of irrigation varied from 0.097 to 0.224kg/m3.

Parthasarathi *et al.* (2017) reported that the drip irrigation increase in water productivity with water saving of 27.40% over the conventional aerobic rice cultivation. Rao (2017) found that the total quantity of supplemental irrigation provided through drip irrigation is 291.42mm where as in conventional practice an amount of 553.30mm was applied, which indicates not only saving in water but also the electricity consumption by about 58 per cent.With the advancement in designing and reduced cost of materials, drip irrigation is becoming popular and acceptable for most of the field crops. It is now realized that drip irrigation not only boosts up the production but also reduces the water requirement, when it is practiced along with fertigation. Drip irrigation for aerobic rice found better in growth and yield of aerobic rice was proved from the recent works of Parthasarathi *et al*. (2012); Vanitha and Mohandass (2013) and Vanitha (2008).

Soman (2012) found that flood irrigation recorded 3.10 tons yield per acre and 9.5 million liter per acre water use while rice through drip irrigation recorded 3.80 tons yield per acre and water use 3.20 million liter per acre.

Kumar (2011) explain the advantages of drip irrigation are: No fertilizer nutrient loss due to localized application, high water distribution efficiency, leveling of the field not necessary, only root zone is saturated, moisture always at field capacity in the root zone, soil factor plays less important role in frequency of irrigation, no soil erosion, highly uniform distribution of water *i.e*., controlled by each nozzle, low labour cost and fertigation can be adopted with drip irrigation.

Zimmerman (2011) reported that rice production is possible during the dry season with drip irrigation and that are similar or better than flood irrigation. However, the variety Bengal produced more rice under the flooded paddy system than the drip irrigation. Rice can be successfully grown in the Virgin Islands with drip irrigation and have yield compared to a flooded paddy system.

The water used in drip irrigation was 905 ha-mm as compared to 2090 ha-mm in puddled transplanted rice. The main reasons for higher water saving under drip irrigation are due to reduced crop duration of 10-12 days across the varieties and precise use of water (Nagaraju *et al.,* 2014).

The literature published on drip irrigation systems in rice across the world were collected, studied and synthesized. Results the dominant system of rice production is transplanting or direct-seeding of rice and keeping the fields flooded with 5–10cm water throughout the growing season. In such systems, it was estimated that farmers use around 15000 liters of water to produce one kg of rice while the maximum requirement is around 4000 liters. A 10% reduction in water use of irrigated rice would free 150000 million m3, which can be used for other needs or for bringing additional land under irrigated crop production. The major hindrance for the wide adoption of drip irrigation system by irrigated rice farming community is the initial investment cost. (Rao and Ladha, 2011).

Yadav *et al*. (2010) revealed that depicted total water use and water use efficiency in different irrigation schedules. The maximum water use was recorded under flood irrigation (785mm) followed by drip irrigation at 1.0 ETc (680mm) and furrow irrigation (659mm). Drip irrigation at 0.6, 0.8 and 1.0 ETc saved 38.9, 25.9 and 13.40%water over that of flood irrigation.

Ibragimov *et al*. (2007) compared drip and furrow irrigation, obtaining that 18-42%of the irrigation water was saved with drip systems in comparison with furrow and the IWUE increased by 35-103%compared with furrow irrigation. Same comparisons were made by Maisiri *et al.* (2005) in a semi-arid agro tropical climate of Zimbabwe; in this study, drip irrigation used about 35%of the water used by the surface irrigation systems, providing higher IWUE. The gross margin level for surface irrigation was lower than for drip irrigation.Vanitha (2008) evaluated the values of water productivity and showed significant improvement with the drip fertigation system in the aerobic environment. Vaithilingam (2013) district manager of *Jain Irrigation Systems* that set up drip in this field said raising an acre of rice would require 13 lakhlitres of water under conventional method. Under drip, it requires only about 4 lakhlitres.

Results from last 5 years work clearly showed the positive effect of drip fertigation for paddy cultivation. However basic studies are required to show other benefits like effect of drip in methane emission, nitrate dynamics etc. Fertigation schedule needs to be standardized and effects of changing nutrient scenario and its economics have to be studied for preparing standard package of practices. Economic analysis of the results indicated a B: C ratio of 1.50 to 2.20 for drip fertigated crop (Soman, 2009).

IWMI and Jain Irrigation Systems Limited (JISL) have conducted rice drip irrigation research trials in farmers' fields at Chinnaganapur village (Kulcharam Mandal) of Medak district, Andhra Pradesh. Two seasonal research trails with rice (MTU 1010) were conducted during the *Rabi* and *kharif* seasons of 2010-2011. Drip system used with 4.0l/h emitter at 50cm intervals for medium and 40cm interval for light soils. Ventury device was installed for fertigation purposes. The results showed that the improved plant growth has resulted in increased number of tillers compared to the flood irrigation. Application of fertilisers has also reduced by adopting drip fertigation schedules at different stages of crop growth (Palanisami *et al.,* 2011).

[Govindan](http://www.cabdirect.org/search.html?q=au%3A%22Govindan%2C+R.%22) and Grace (2012) conducted field experiment to study the Influence of drip fertigation on the growth and yield of rice varieties (*Oryza sativa* L.). The increase in rice grain yield with drip irrigation at 150%PE + drip fertigation of 100%RDF + azophosmet + humic acid was mainly attributed by greater and consistent availability of soil moisture and nutrients which resulted in better crop growth, yield components and ultimately reflected on the grain yield.

Parthasarathi, *et al*. (2012) suggested that the lateral spacing of 0.80m with 1.0 l/h drippers when the plants spaced at 20cm×10cm + SDI through fertigation is adjudged as the best treatment for aerobic rice cultivation in enhancing the values for water productivity and grain yield in the areas of limited water availability.

Lafitte *et al*. (2002) reported that the significantly higher grain yield was recorded in lateral distance of 0.80m, row spacing of 20cm with dripper flow rate 1.0 l/h + 30% more water on surface treatment (4249kg/ha) followed by lateral distance of 0.8 m, row spacing of (5×20×30×20×5)cm with dripper flow rate 1.0 l/h 30% more water on surface (4171kg/ha), lateral distance of 0.8m, row spacing of 20cm with dripper flow rate 1.0 l/h (4152kg/ha), lateral distance of 0.8m, row spacing of (5×20×30×20×50cm with dripper flow rate 1.0l/h (4039kg/ha) and lower yield was observed in treatment conventional irrigation at IW/CPE ratio of 1.25 at 30mm depth of irrigation (3523kg/ha).

Micro irrigation is a general, broadly defined term and means slow application of water on or below the soil surface. It can be also called localised irrigation, to emphasize that only part of the soil volume is wetted (Lamm *et al*., 2007). Micro irrigation systems can be classified as a surface drip, subsurface drip, bubbler and micro sprinklers systems. Drip irrigation is, according to ASAE, 2007, defined as a ˝*method of micro irrigation wherein water is applied to the soil surface as drops or small streams through emitters. Discharge rates are generally less than 8 L/h for single-outlet emitters and 12 L/h per meter for line-source emitters˝*. In the literature, trickle irrigation is used interchangeably with drip irrigation. In this work the term drip irrigation will be used.

After the World War II the technological development on an industrial scale came about with the ˝plastic revolution˝, initially it started in glasshouses in England, between 1945-1948 and later in Israel and in the USA (Dasberg and Or, 1999). Equipment for installing subsurface drip had been developed by the 1970s. About the same time surface drip irrigation systems, including fertilizer injection were being developed in Israel. When tubing and drip emitters became more reliable, surface drip irrigation systems grew at a greater rate than subsurface systems. This was because of problems with root intrusions and emitter clogging of the latter (Camp, 1998). After Reinders, 2007, the area irrigated by microirrigation in the world increased from 436,590 ha in 1981 to more than 6.089,534 ha in 2006.

**1.8 Design**

Drip irrigation systems are designed to transport water from source, to a crop, through a delivery network of a pipes and emission water devices. The general goal of drip irrigation system design is to provide irrigation water efficiently and uniformly to a crop, to help meet the evapotranspiration (*ET*) needs. At the same time, maintaining desired water content at a depth of the root zone, which is increasing the crop yield and quality, is of great importance (Lamm *et al*., 2007; FAO, 2002a).

When the field is cropped, water can be lost from the soil surface and wet vegetation through evaporation (*E*). The process is affected by Climatological factors such as solar radiation, air temperature, air humidity and wind speed. The second process of water loss is called transpiration (*T*), where liquid water from the plant tissues vaporizes into the atmosphere through stomata, located on the plant leaves. Transpiration, like evaporation, depends on the energy supply, vapour pressure gradient and wind. Air temperature, air humidity, solar radiation, and wind speed should be considered when assessing transpiration. Transpiration rate is also determined by many other factors, such as crop characteristics, cultivation practices, environmental aspects, soil salinity, waterlogging and the soil water content, and its ability to transport water to the plant roots. When those two above mentioned separate processes, where water is on one hand lost from evaporation from the soil surface and, on the other hand, when water is lost from transpiration from a plant, combined they are called evapotranspiration (*ET*).

Evaporation and transpiration occur together, and distinguishing between them is not easy. At the beginning of the crop growth, while the crop is small, the main process is evaporation. Later in crop development, or when the crop is fully grown, it completely covers the ground and then transpiration becomes the prevailing process. It has been estimated that at crop sowing, 100% of the total *ET* comes from evaporation. But when the crop develops its full cover, evaporation accounts for only about 10% of *ET* and transpiration for the remaining 90%. Crop water requirements encompass the total amount of water used in evapotranspiration (FAO, 2002b).

Irrigation requirements (*IR*) refer to the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements. In this case the *ETc* (crop water requirements) have to be calculated by multiplying *ETo* (reference crop evapotranspiration), which is defined as the evapotranspiration from a reference surface, not short of water, with crop coefficient (*Kc*), which varies with the crop, its growth stage, growing season and weather conditions. If irrigation is the sole source of water supply for the plant, the irrigation requirement will always be greater than the crop water requirement to allow for inefficiencies in the irrigation system. If the crop receives some of its water from other sources (rainfall, water stored in the ground, upward seepage, etc.), then the irrigation requirement can be considerably less than the crop water requirement. (Dorenbos *et al*., 1984; FAO, 2002b).

Once the crop water irrigation requirements are considered, irrigation scheduling can be prepared. Scheduling has to integrate all elements of the system’s hydraulic design and maintenance with various aspects of the soil and the crop characteristics with the atmospheric evaporative demand. In short, drip irrigation scheduling is controlled by measuring or estimating of crop water needs, soil water status and plant water status property (Lamm *et al*., 2007). As noted in FAO (2002a), many factors influence the soil water movement, its water holding capacity and plant ability to use water the drip irrigation system used has to match most of them.

The primary objective of a drip system design is to choose appropriate components and layout to achieve suitable water distribution over the field and, at the same time, meet crop need with consideration of economical, operational, water quality and quantity. Well designed drip irrigation systems should provide equal soil water availability to all plants in the irrigated field at high irrigation efficiency (in ASAE, 2007 is defined ˝*as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied, expressed as a percentage˝*). Water distribution, by drip irrigation systems, can be applied as a line source or point source applications for both tapes and tubings. Line sources apply water in a continuous or near-continuous pattern along the length of the lateral. In this category are soaker hoses or porous pipes (line-source emitters) in which the entire pipe wall is a seepage (and filtration) surface, as well as drip tapes with closely spaced (e.g., 15-30 cm) emission points whose water application patterns overlap. Polyethylene drip tubing, with on line, or built in, or fused drip emitters, is most commonly used. Thin walled collapsible emitting hoses, also called drip tapes, are used to irrigate annual crops, but seldom used for irrigation of permanent crops because these drip lines don’t have the longevity required. Point source emitters can be grouped based on their flow characteristics. Thin walled driplines with periodically spaced emitters infiltrate upon pressurization. Emitter spacings are ranging from about 50 mm to 1m. The combination of emitter discharge rate and emitter spacing determines the dripline discharge rate (L/h-100 m). Water discharge from the emission points which are spaced more than 1 m apart (usually 1 m or more) is called point source application. Water discharged from closely spaced outlets is called line-source application. These devices apply water at discrete points, and overlap between wetting patterns may or may not occur, depending on emitter spacing, irrigation duration, and emitter flow rate (Evans *et al*., 2007; Lamm *et al*., 2007).

Preliminary design steps therefore include: determination of crop water requirements, irrigation requirements, leeching requirements, percentage wetted area, number of emitter per plant and emitter spacing, irrigation frequency and duration, emitter selection, design emission uniformity and allowable pressure variation (FAO, 2002a).

**1.9 Soil Water Distribution under Surface Drip Irrigation**

Factors such as soil hydraulics, water quantity, crop properties have a strong influence on the selection of the emitters, their spacing and tubing size. Based on this it is clear that information about the dimensions of the wetted zone in the soil which forms beneath the emitter(s) is an important prerequisite at the beginning of the drip irrigation design process.

**Importance of wetted volume**

The distances between the emitters along the laterals have to be adapted to crop water requirements. Distances should be based on soil hydraulic properties and emitter discharge rate (*Q*). The knowledge about wetted soil volume shape in relation to peak crop water requirements, crop root zone extend and irrigation frequency can be considered as a unifying design objective for various emitter layouts, discharges and spacings. The plant root water uptake during water infiltration into the soil is, at the design stage, usually neglected (Dasberg and Or, 1999). The selection of optimum emitter spacing is not an easy matter, considering all the variables (which usually have nonlinear relationship) involved. In recent years a number of physically-based, analogue and mathematical models have been developed to help estimate wetting patterns dimensions from a point source.

At the stage of surface drip irrigation system installation, the placement of the emitters above the soil surface causes water infiltration within a very small area compared to the total soil surface area. According to Vermeiren and Jobling, (1984), Cote et al. (2003), Gardenas *et al.* (2005), Skaggs *et al.* (2010), the shape of the wetted soil volume under single drip emitter is influenced by soil hydraulic properties, soil texture, soil structure, impermeable layers in the soil profile and anisotropy such as horizontal and vertical permeability. The soil wetting and drying are continuous processes under cropped conditions. In this case the soil water content patterns depend also on water management (volume of water applied per irrigation, the rate of application, irrigation frequency), emitter distance (number of drippers), dripper placement (above or below soil surface), initial soil water content and lateral positioning with respect to the plant row. According to Benami and Ofen (1995) the wetted zone beneath the surface point source emitter consists of three phases (Figure 2). Around and under point source emitter a transition zone forms in which the soil water content is near saturation and soil is poorly aerated. Around the transition zone a wetting zone forms. In this zone the water spreading is governed by capillarity and gravitational forces and the water content decreases with the distance from the point source. The third zone is the wetting front, where the soil water content equals the initial water content.



**Fig. 2. Phases of water distribution in the soil profile for two soil types from a point source emitter at a low discharge rate (Benami and Ofen, 1995)**

As mentioned by Lamm *et al.* (2007) the monitoring, management and modelling of water distribution in the soil under cropped conditions requires also information on patterns of plants root water uptake. Root water uptake patterns influence water distribution in the soil profile and are essential for obtaining reliable information of water and matric potential distributions within the volume of wetted soil. Root water uptake information is important for drip irrigation design purposes. Irrigation system emitter spacing, application uniformity and discharge rate have to match with the extent of plant root system.

The knowledge acquired on other irrigation systems cannot be directly applied to drip irrigation. Usually, because of the lack of necessary financial resources or time, it is difficult to carry out experiments with all possible drip irrigation design factors and scheduling strategies under specific field conditions to determine the optimal soil wetting. Hence, scientists developed various models to describe water dynamics in the soil which can be used to evaluate a series of possible drip irrigation scheduling strategies. The most promising modelling strategies could be selected and tested under field conditions.

Lubana and Narda (2001) and more recently Subbaiah (2011) presented an extensive review of models of soil water dynamics during drip irrigation. They pointed out that knowledge gaps still exist in the field of water dynamics in the soil under drip irrigation. Possible improvements on this topic include more fieldwork experiments to supplement modelling progress.

**2.0 Influence of Drip System design and Management on Soil Water Distribution**

Wang et al. (2006) carried out a research on the effect of drip irrigation frequency on potato growth and wetting patterns dimensions. He used six different drip irrigation scheduling strategies (irrigation once every day (N1), once every two days (N2), once every three days (N3), once every four days (N4), once every six days (N6) and once every eight days (N8)). Equal amount of water was applied for all frequencies studied. The results showed that water distribution, wetted soil depth and distance from the emitter were affected by different irrigation frequencies. Distribution of water varied with the potato growth stage. In the middle of the potato growing season, at the depth greater than 30 cm, decreased irrigation frequency increased water content variations. During the late growth stages the treatment N8 showed larger variation at the depth of 50 – 90 cm in comparison to other treatments. This happened because of longer water application duration, which extended soil wetting pattern in the horizontal direction. Also, more water was depleted at that depth because of denser root system. Higher irrigation frequency caused higher root length density at the soil depth of 0 – 60 cm and the lower root system density at 0 – 10 cm. Results also showed that irrigation frequency reduction (from N1 to N8) resulted in significant yield reduction.

Li *et al*. (2003) studied the effect of a surface point source emitter *Q* and volume of applied water on the shape of the wetted area in a loam soil. The emitter discharge rates varied from 0.6 to 7.8 L/h. Results showed that the wetting front moved fast at the beginning and slowed down with increasing time. The saturated wetted radius at the soil surface increased with increase of discharge rate. The wetted radius and depth at the soil surface were proportional to the volume of applied water. Radius of saturated water entry zone become larger as time increased, and after around 3.5 h approached to a constant size. The constant surface saturated wetted radius was reached faster with the higher emitter *Q*. Higher discharge rate resulted in faster wetting front movement in all directions. Emitter discharge rate increase, after adding the same volume of water, resulted in a wetting pattern increase in the horizontal direction and decrease in the vertical direction. The same results were reported from other studies too (e.g. Khan et al.*,* 1996). Also, the increase in volume of applied water increased the wetting pattern depth and had little effect on wetting pattern horizontal directions. Li et al. (2004) studied the wetting pattern movement in sand and loam soil and concluded that the increase in emitter discharge rate allowed more water to redistribute in the horizontal direction when the same volume of water is applied. Emitter *Q* decrease caused more water to redistribute in the vertical direction.

Ah Koon *et al.* (1990) studied the effect of three emitter discharge rates (1, 2 and 3 L/h) on the water distribution and drainage beneath a sugarcane crop compared to fallow plot on clay and silty clay soil. Similar to results of Li et al. (2003, 2004) increase of emitter *Q* increased lateral water spreading.

Also the distribution of water was studied by Bar-Yosef and Sheikholslami (1976). In their research a sand soil was irrigated with a surface drip source. Their results showed that when adding the same amounts of water and increasing the emitter *Q* at the same time, the wetting pattern size in vertical direction increased and decreased in horizontal one.

Mostaghimi *et al.* (1981) also studied water movement in silty clay loam soil under single emitter source. He carried out a laboratory experiments and showed that emitter discharge rate increase results in a wetting pattern increase in the vertical direction and a decrease in the horizontal direction.

Bresler et al. (1971) examined the surface drip emitter discharge rate effect on the distribution of water content in sandy and loamy soil. He carried out field and laboratory experiments which showed that emitter discharge rate increase caused in larger wetted area in horizontal direction and decreased soil wetted depth. Research done by Levin et al. (1979) for sand soil, confirmed the findings of Bresler et al. (1971).

Acar et al. (2009) investigated the effect of emitter discharge rate and volume of applied water under drip irrigation for loam and clay loam soil. The emitter discharge rates examined were 2 and 4 L/h. Results showed that different discharges did not have significant effect on the size of the wetting pattern. However, different amounts of applied water significantly affected vertical wetted front size, but had no significant effects on later soil water movement within the soil profile and on the soil surface. The results also showed that the wetted volume increased with higher emitter discharge rates affecting both vertical and lateral soil water movement.

Thabet and Zayani (1998) carried out a study with a loamy sand soil to determine the effect of different surface drip emitter discharge rates (1.5 and 4 L/h) on the size of the wetting pattern. They concluded that at the given amount of water applied low water application rates extend the wetting pattern in horizontal direction and high application rates in vertical direction.

Badr and Taalab (2007) concluded that when applying the same amount of water, the higher *Q* causes more water to spread in horizontal direction and while decreasing the discharge rate causes more water to spread in vertical direction. The study was carried out under active root water uptake of tomato plants growing on sandy soil.

**2.1 Guides for estimating percentage of wetted area**

The percentage of wetted area is the average horizontal area wetted within the upper 30 cm of the crop root zone in relation to the total area which is cropped. Many times the question of how many emitters per plant are required arises and this number will depend on the desirable percentage wetted area and the area wetted by one emitter.

Keller and Bliesner (1990) presented a Table for estimating the wetted area (Aw). The estimation is based on a standard 4 L/h emitter for different soil types and depths. They stated that the Aw, wetted by one emitter at the soil surface, is usually less than half as large as Aw measured at a depth of 15 to 30 cm. They provided the values for different soil texture classes, soil depths and degrees of soil stratification. The values are based on daily or every-other-day irrigations, which apply sufficient volumes of water to slightly exceed the water crops need. Wetted area is approximated by a rectangle; the long dimension, w, is the expected maximum horizontal diameter of the wetted soil volume caused by one emitter. Se is the short dimension and is representing 80 % of maximum expected diameter. Se represents the emitter spacing, which should give a continuous wetted strip of soil. If those two values are multiplied, the result is approximately the same as the circular wetted area. As clearly stated by the authors, these values should be used as guidelines only.

**2.2 Field and Laboratory Studies**

Li *et al*. (2003) studied the effect of discharge rates and applied volume of water on the shape of the wetted area, from a surface point source for a loam soil. The application rates varied from 0.6 to 7.8 L/h. Results for surface and vertical wetting for all experiments showed that the wetting front moved fast at the beginning and slowed down with increasing time. The wetting front moved outward in a circular arc shape and the surface saturated wetted radius increased with increase of application rate. The surface wetted radius and wetted depth were proportional to the volume of water applied. Saturated water entry zone radius become larger as time increased, and approached a constant value after around 3.5 h. The bigger the application rate, the faster the constant surface saturated wetted radius was reached. Higher application rate resulted in faster wetting front movement in both, radial and vertical directions. Increase in application rate after adding the same volume of water, resulted in an increase in the horizontal direction and decrease in the wetted depth, which has been reported from other studies (e.g. Khan *et al.,* 1996). In addition, the bigger volumes of water applied produced higher water content within the wetted volume. Increase in the applied volume of water increased the wetted depth and had little effect on horizontal wetted area. Li *et al.* (2004) followed his work from Li *et al.* (2003) but this time he monitored the wetting front movement in sand soil too and concluded that for the same volume applied, the increase in application rate allowed more water to be distributed in the horizontal direction. A decrease in application rate allowed more water to distribute in the vertical direction. They mentioned that further research is necessary to verify whether those results are true in other soil types.

Similarly, Ah Koon *et al.* (1990) studied three emitter discharge rates (1, 2 and 3 L/h) on the distribution and drainage of water beneath a sugarcane crop and fallow plot on clay/silty clay soil. Results showed that higher emitter discharge rate (4 L/h) increased lateral spread of water and are in agreement with Li *et al.* (2003, 2004) results.

Bar-Yosef and Sheikholslami (1976) studied the distribution of water in sand soil, irrigated from a surface drip source. They found that, when adding identical amounts of water, but increasing the emitter discharge rate, the wetting depth increased and horizontal water movement decreased.

Bresler *et al.* (1971) studied the effect of surface emitter discharge rate on the water content distribution in loam and sand soil. Laboratory and field experiments showed that increase in emitter discharge rate resulted in increased wetted area in horizontal direction and decreased soil wetted depth. Research done by Levin *et al.* (1979) for sand soil, confirmed the findings of Bresler *et al.* (1971).

Study about effect of drip irrigation frequency on wetting pattern and potato growth was done by Feng-Xin Wang *et al.* (2006). They used six different irrigation frequencies (once every day (N1, once every two days (N2), once every three days (N3), once every four days (N4), once every six days (N6) and once every eight days (N8)). They applied equal amount of water for all studied frequencies. The results showed that irrigation frequency affected water distribution, wetted soil depth and distance from the emitter. Water distribution varied with the potato growing stage. The wetting pattern developed under treatment N1, showed larger change than those for N4 and N8. In the middle of the planting season, at the depth below 30 cm, water content variations increased as irrigation frequency decreased. During the late growth stages the treatment N8 showed larger variation at depth of 50 – 90 cm than other treatments. This was due to longer application duration, which led to larger wetted soil in the horizontal direction. Denser root distribution at that depth depleted water more quickly. The higher the frequency, the higher the root length density in 0 – 60 cm of soil depth and the lower root length density at 0 – 10 cm of soil depth. Also the reduction in irrigation frequency from N1 to N8 resulted in significant yield reduction.

**2.3 Empirical Models**

For prediction of wetting patterns from a point source a number of models exist. We can group them in empirical, analytical or numerical models.

Empirical models have been developed, based on field observations or regression analysis. Keller and Karmeli (1974) presented a table which serves as a guide for estimating an average percentage of wetted area (Pw). As already mentioned earlier, the optimum value for Pw is unclear; but, considering the current state of knowledge, the Pw for widely spaced crops should be held below 67%. But for closely spaced crops (crops spaced less than 1.8 m apart) Pw can approach to 100%.

Schwartzman and Zur (1986) developed a semi-empirical model for determining width and depth of the wetted soil volume under the point source. Wetted soil volume was assumed to depend on the hydraulic conductivity of the soil (*Ks*), on emitter discharge rate (*Q*) and on the total amount of water in the soil (V). Using dimensional analysis, analytical expressions for wetted depth and width were obtained as functions of the above parameters. The equations coefficients were then obtained empirically based on experiments carried out on two types of soils (Gilat loam and Sinai sand). This model is one of the most practical for determination of soil wetted geometry for point sources. However, using the model for a wide range of conditions is questionable because it was calibrated only on two sets of experimental data, with only two soil types and two emitter discharge rates.

Kandelous and Šimůnek (2010a) compared the above two empirical models of Schwartzman and Zur (1986) and Amin and Ekhmaj (2006) against field data, to evaluate their accuracy in predicting wetted zone dimensions. Results showed better prediction capability of the Amin and Ekhmaj (2006) model in comparison with the Schwartzman and Zur (1986) model. In some cases the Amin and Ekhmaj (2006) model predicted wetting pattern geometry even better than the numerical models results. The better predictive capability of the Amin and Ekhmaj (2006) model can be explained by its use of *Δθ*. Kandelous and Šimůnek (2010a) concluded that soil water content plays an important role when predicting wetted geometry for surface drip irrigation systems.

**2.4 Analytical Models**

Analytical models for prediction of geometry of wetting patterns, under surface point source, usually solve the governing water flow equation under specific conditions. Analytical models rely on assumptions, such as soil homogeneity, and they do not take into account root water uptake.

Cook *et al*. (2003) developed a user friendly Microsoft Windows-based software programme, WetUp, that provides visualisation of the wetting patterns (Figure 2.2). The programme estimates dimensions of the wetting patterns, in different soil textures, with different soil hydraulic characteristics, for surface or subsurface point sources (emitters).

WetUp contains a database of predefined soil types, emitter flow rates (from 0.503 to 2.7 L/h), application times (1 – 24 h), initial soil moisture conditions (3, 6 and 10 m of suction) and emitter position (surface or subsurface).

WetUp uses a Philip’s (1984) solution for flow from a surface and subsurface point source. The solution determines the travel time of water and is based on a quasi-linear analysis of steady three dimensional unsaturated water flow.

Kandelous and Šimůnek (2010a) compared WetUp to other empirical and numerical solutions, for estimating the size of the wetting pattern. WetUp predictions of the geometry of the wetting pattern were less precise compared to Amin and Ekhmaj (2006) or numerical model Hydrus-2D (Šimůnek *et al.,* 1999). Cook *et al.* (2003) also reported that WetUp tends to underestimate horizontal wetting at large volumes of water applied for coarse textured soils.

Other analytical solutions have been derived for steady infiltration from a buried point source and from cavities (Philip, 1968, 1984), from a surface point (Warrick, 1974), and, from shallow circular ponds (Wooding, 1968). Mmolawa and Or (2000) presented a semi-analytical model for calculating water flow and non-reactive solute transport with and without plant uptake for a buried or surface point source.

Application of analytical models in trickle irrigation management is limited because the solutions are based on limiting assumptions with regards to source configurations, the linearization of the flow equation and homogeneous soil hydraulic properties. Most of them also do not take into account root water uptake.

**2.5 Numerical studies**

There are a number of numerical models developed with the purpose of simulating the surface and subsurface point source water infiltration. Brandt *et al*. (1971) developed a model to analyse multidimensional transient infiltration from a trickle source. Bresler *et al*. (1971) compared the theory, discussed by Brandt *et al*. (1971), with experimental results. Calculated and measured locations of wetting fronts and soil water content distribution were examined. They concluded that, despite the dissimilarity between the theoretical and experimental results, the agreement is sufficient for the practical implementation of the theory.

In 1975 Bresler reported a study about numerical model simulations for analysis of multidimensional simultaneous transfer of a non-interacting water and solute transport, applicable to the infiltration from a trickle source. Mostaghimi *et al*. (1982) studied water movement in silty clay loam soil under single emitter source. They used the numerical method of Bresler (1975) and compared it to laboratory experimental results. The study showed that increasing discharge rate of an emitter results in an increase in the vertical direction and decrease in horizontal direction of the wetted zone. Those results are in contraindication with the results of Li *et al*. (2003), Bar-Yosef and Sheikholslami (1976) and Khan *et al*. (1996). Bresler (1975) also found quite good agreement between predicted and measured soil water content. Lafolie *et al*. (1989) presented the numerical solution which allows predictions of water content distribution under drip irrigation.

Šimůnek *et al.* (1996) developed a software package, Hydrus-2D, which was updated to provide a third dimension, now called Hydrus-2D/3D (Šimůnek *et al.,* 2006). The software enables implementation of three-dimensional water flow, solute transport, and root–water and nutrient uptake based on finite-element numerical solutions of the flow and transport equations. For the water flow module, the program numerically solves Richards equation (Richards, 1931) for variably saturated flow. The flow equation also incorporates a sink term to simulate water uptake by plant roots. In 2011 a 2.0. version of Hydrus-2D/3D has been released. It includes many new features as compared to version 1.0. The most important ones, which can be used for simulating drip irrigation design and management, are various new boundary conditions (i.e. surface and subsurface drip irrigation) and triggered irrigation (irrigation can be triggered by the program when the pressure head drops below specified value) (Šejna *et al*. 2011). The main unit of the programme is the Hydrus graphical user interface (GUI) which defines the overall computational environment of the system.

Soil-water flow and solute transport modelling are useful for water resources and ecological management and, due to the increasing computer speed and availability of more comprehensive numerical models, Hydrus-2D/3D is now increasingly being used for evaluating water flow in trickle irrigation systems. The number of such studies is extensive and has been growing steadily in recent years (Assouline, 2001; Schmitz *et al*., 2002; Cote *et al*., 2003; Skaggs *et al*., 2004; Lazarovitch *et al*., 2005, 2007; Fernandez-Galvez and Simmonds, 2006; Dahiya *et al*., 2007; Provenzano, 2007; Patel and Rajput, 2008; Elmaloglou and Diamantopolus, 2009; Kandelous and Šimunek, 2010a, b; Rodriguez-Sinobas *et al*., 2010; Skaggs *et al*., 2010). Some of these studies simulated subsurface drip irrigation (SDI) process as a line source (a lateral) (Ben-Gal *et al*., 2004; Skaggs *et al*., 2004;Patel, 2008), while others simulated SDI by means of a point source, as individual emitter (Lazarovitch *et al.*, 2005; Provenzano, 2007; Kandelous and Šimůnek, 2010a, b). While some other authors assessed the ability of Hydrus to simulate water movement from surface drip irrigation systems (Assouline, 2001; Gardenas *et al*. 2005), the number of studies on surface drip irrigation has been limited by the lack of appropriate boundary conditions (a problem which is now resolved by the introduction of version 2.0 in 2011). All of these studies were done using either planar or axisymmetrical two-dimensional models, which is valid as long as the flow domain studied is not influenced by neighbouring emitters.

Kandelous *et al.* (2011) used Hydrus-2D/3D to analyse field data, assuming the modelling approaches in which emitters were represented, either as a point source in an axisymmetrical two-dimensional domain, a line source in a planar two-dimensional domain or a point source in a fully three - dimensional domain. Results showed, that SDI systems can be accurately described, using an axisymmetrical two-dimensional domain, only before wetting patterns start to overlap, and a planar two-dimensional domain, only after full merging of the wetting fronts from neighbouring emitters. Fully three-dimensional model appears to be required to entirely describe the subsurface trickle irrigation process.

Kandelous and Šimůnek (2010a) compared numerical, analytical and empirical models to estimate wetting patterns for surface and subsurface irrigation. They evaluated the accuracy of several approaches used to estimate wetting zone dimensions by comparing their predictions with field and laboratory data, including the numerical Hydrus-2D model, the analytical WetUp software and selected empirical models (Schwarzman and Zur, 1986; Amin and Ekhmaj, 2006; Kandelous *et al*., 2008). They used the mean absolute error to compare the model predictions and observations of wetting zone dimension. Mean absolute error for different experiments and directions varied from 0.9 to 10.4 cm for Hydrus, from 1 to 58.1 cm for WetUp and from 1.3 to 12.2 cm for other empirical models.

Skaggs *et al*. (2010) used numerical simulations with Hydrus-2D to investigate the effect of application rate, antecedent water content and pulsed water application on horizontal water spreading from drip irrigation emitters. Results showed that higher antecedent water content increases water spreading from trickle irrigation systems, but the increase is bigger in a vertical than a horizontal direction. Also, lower application rates and pulsing, produced minor increases in horizontal spreading of water. Some irrigation treatments were tested in field trials and they confirmed the simulation results. Overall they found out that soil texture (hydraulic properties), and antecedent water content largely determine the spreading and distribution of a given water application, with pulsing and flow rate having very little effect.

Cote *et al*. (2003) also used numerical model Hydrus -2D to investigate the effect of pulsed water applications on the size of the wetting pattern for subsurface drip irrigation for sand, silty and silty clay loam soils. They found that soil hydraulic properties greatly influence the geometry of wetting pattern. Irrigation frequency (pulsing) has slightly increased the dimensions of the wetting pattern in highly permeable coarse textured soil. Also, similarly to Skaggs *et al*. (2010), high discharge rates from a SDI tend to increase vertical spreading more than horizontal. The simulations also highlighted that, in order to achieve desired wetted volume, the drip irrigation system discharge rate has to be regulated according to particular soil type and consequently its hydraulic properties are of great importance.

Assouline (2001) presented a study about the effect of different emitter discharge rates, including micro drip emitters (emitter discharge rate <0.5 L/h), on different water regimes in drip irrigated corn. In his study, three emitter discharge rates (0.25, 2.0 and 8 L/h) were compared in field experiments and for numerical simulations using Hydrus-2D. Field experiments showed that, under microdrip irrigation, the highest relative water content occurred in the upper 30 cm of the soil profile and the lowest in the 60 to 90 cm layer. Numerical results showed that, under microdrip irrigation treatment, wetted volume of soil was smallest in both, horizontal and vertical directions. The water content gradients for microirrigation treatment were also less extreme in both directions, compared to 2.0 and 8.0 L/h discharge rates. The saturated zone of soil was maintained only beneath the 8.0 L/h dripline. The depth of the wetting front below the dripline was shallowest under microdrip irrigation treatment.

Those results are in agreement with findings of Mostaghimi *et al*. (1982) but in contradiction with Khan *et al*. (1996) and Li *et al*. (2003) which concluded that higher emitter discharge rates extend soil water movement in a horizontal direction. This was likely to be caused by the differences in hydraulic properties of different soils or water uptake patterns of plant.

**2.6 Drip network**

**Manufacturing variation of distributors**

The parameter that describes the anticipated variation of discharges of a set of new distributors caused by the variation in the manufacturing of the distributors is called manufacture’s coefficient of variation. Thus, the coefficient of variation (CV) is calculated as the ratio of standard deviations of the discharges to the average discharge rate of the distributors (drippers) of a set of at least 50 numbers following at reference pressure head as stated below (Biswas, 2015).



Where, CV=coefficient of manufacturing variation for the set of emitters in which are the individual discharge rates, l/h.

n=number of emitters in the sample

= average discharge rate of the sample ()/n, l/h

= standard deviation of the discharge rate of the emitters

**Table 1** Classification of manufacturer’s coefficient of variations

|  |  |
| --- | --- |
| Coefficient of Variation (CV) | Interpretation |
| 0.05 or less | Good |
| 0.05-0.10 | Average |
| 0.10-0.15 | Marginal |
| 0.15 or more | Unacceptable |

Source: Biswas (2015)

**Uniformity of emission**

The uniformity of emission of the drippers were determined by the discharges as recorded under the standard operating pressure following Keller and Karmeli (1974) as stated below:



Where, qmin= (1-3CV)

=the average discharge rate of all the pressure

Mr=the manufacturer’s discharge ratio

f (e)=the adjustment factor for number of distributors per plant

**2.7 Determination of Width and Depth of Wetting under Drip Irrigation**

**Measurement of Width of wetting**

After the prescribed irrigation intervals for each discharge rates, the width of wetting for each discharge rate was measured as follows:

* The whole area of wetting was divided into four parts by two intersecting line meet each other at right angle at the point of application of irrigation water i.e. almost at the centre of wetting zone.
* The width of wetting was measured at every point at 15 cm apart on the two intersecting line starting from the centre and continued to the front of wetting.

**Measurement of depth of wetting**

The depth of wetting was measured for the two discharge rates using the soil auger as follows:

* The depth was measured on different points which are 15 cm apart from each other on the two intersecting lines drawn on the wetted area.
* The measurement was started from the centre of the wetted area which is the point of application of water from the emitter.
* The auger was inserted at different points of measurement at 15 cm apart from each other on the line.
* By observing the soil on the tips of the auger, the depth of wetting was determined and noted it down for different points on the line of the wetted area.

**Schwartzman and Zur (1986) Equation for determination of Width and Depth of Wetting under Drip Irrigation**

The equation is given as:

**Zf = k1 (Vw) 0.63 ( ) 0.45**

**Wf = k2 (Vw) 0.22 ( ) -0.17**

Where**, Zf =** vertical distance to wetting front, m

**Wf** = Wetted width or dia. of wetting front

**k1** = empirical coefficient = 29.2

**Vw**= Volume of water applied, litre

**ksat** = Saturated hydraulic conductivity, m/s

**q** = Emitter discharge, lph

**k2** = Empirical coefficient = 0.031.

**2.8 Conclusion**

The decreasing availability of water to agriculture sector has become a serious limitation in many areas, particularly in South East Asia. The share of water for agriculture is expected to reduce further with the increasing demand from other sectors. This necessitates efficient use of water and nutrients to enhance crop productivity. To counter the deficit without missing the production targets, adoption of micro-irrigation system in India is being considered as a potential alternative. There is also a strong need to try out these technologies in more crops. At present, more than 60 percent of the area under drip irrigation can be attributed to orchids and plantation crops. The challenge lies in popularizing these technologies in major crops such as wheat, mustard, potato, cotton, alfalfa etc. One of the ways of doing this is through finding out the environmental and economic benefits of these technologies in saving water, fuel, power and fertilizer.

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