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Advances in greenhouse irrigation systems: Water-use efficiency, automation and sustainable crop production-a review

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Abstract

Greenhouse cultivation is one of the advanced methods of agriculture in which crops are cultivated in a specific environment to increase productivity and quality. Greenhouse cultivation is quite different from conventional methods of agriculture in that the farmer can control parameters such as temperature, humidity, light intensity, and carbon dioxide levels according to the crop's needs. This helps in protecting the crops from weather conditions, pests, and diseases. Thus, a consistent and high crop yield is obtained throughout the year. In greenhouse cultivation, crops are cultivated in a high-density manner, and the growing medium is limited in volume. Thus, water management is one of the most important aspects of greenhouse cultivation. Irrigation is the primary source of water supply for crops in a greenhouse. Since rainfall is completely excluded in a greenhouse, irrigation is essential for providing water to crops. Proper irrigation ensures that adequate water is provided to crops in the right amount and at the right time, which is essential for crop development and growth. Proper irrigation management in a greenhouse not only increases crop yield but also enhances water use efficiency. In view of water scarcity and competition for water resources, the importance of efficient irrigation systems is on the rise. The conventional methods of irrigation used for open field cultivation are not suitable for green houses due to low efficiency and poor control. For this reason, special irrigation systems have been designed to cater to the specific requirements of greenhouse cultivation. This review article deals with greenhouse irrigation systems and their significance for protected cultivation. The aim of this article is to obtain a clear idea of various irrigation methods, their application, and impact on crop productivity and sustainability.

Keywords: Greenhouse, irrigation, drip irrigation, sprinkler, automated, fogging or misting system

Introduction

Growing plants in greenhouses can lead to too much loss of nutrients from containerized crops grown in soilless substrate if irrigation is not managed properly. The drainage water often has high levels of nitrates, phosphorus, and potassium.The leakage of nitrate and phosphorus from irrigation in greenhouses to the environment was much higher than what environmental guidelines recommend, causing pollution of surface and groundwater (Garcia-Caparros *et al*., 2018) [7]. Assuming the saline water is applied, more or less rapidly ballast ions (eg., sodium (Na+) and chloride (Cl−)) will accumulate dissolved in the water at a higher concentration than in the uptake concentration (i.e. amount of the ion present in the plant in relation to both being taken up by plants) (Massa *et al*., 2010) [17]. In principle, though, seawater irrigation of one species can lead to a subsequent drip line where the drainage used to irrigate other (salt tolerant) crops that follow it in the cropping sequence; whereby using appropriate blending techniques with the primary source of water available for greenhouse operation - if they are sufficiently salt tolerant, then it could be directly used(Garcia-Caparros *et al*., 2018) [7].

Precision agriculture is a term used for which we have technologies that support very specific agricultural practices which in turn we see play out in greater efficiency and less environmental impact (Nikolaou *et al*., 2019). Sujatha *et al*., 2023 [18, 34] was studied about the Comparative study of the impact of saline water irrigation on tomato yield, quality and growth in Andhra Pradesh. In green house-based production we see a 20 to 40% decrease in crop water requirements as compared to traditional field cultivation; also it is a fact that growers put on more irrigation water than what is calculated to be the actual water use (Fernandes *et al*., 2003; Kitta *et al*., 2015; Levidow *et al*., 2014) [5, 11, 13]. The which is put through the system of collection and reusing of drainage water on farms and in greenhouses sees large scale reduction in total volume of water used, also the use of what we may term as high quality (low conductivity) water may be reduced in volume by a process of mixing it with water of lower quality that which has NaCl in it for example. In different countries development of methods for the use of saline drainage water has been reported (Ayars *et al*., 2006; Malash *et al*., 2011; Qadir *et al*., 2004) [3, 16, 21]. These also include what we may term mixed and sequential use which we see across species to species. Mixed use is a mix of two sources of irrigation water which in turn produces irrigation water of better quality and which also increases total irrigation supply. Also it is to be noted that this is not a viable economic solution if the saline water does not at least cover 25% of the total irrigation water requirement(Grattan *et al*., 2003) [8].Blunting drainage water into water of low electrical conductivity (EC) is a practice which has caught on in large parts of Egypt, India, Pakistan, the United States and Central Asia(Tanji *et al*., 2002) [30].In terms of field agriculture we see that which is called sequential reuse of water where better quality water is used for the crop which has the least salt tolerance and then the drainage which results from that field which has a subsurface drainage system is used to irrigate crops which are more tolerant to salt. In California we have seen that this practice is used for trees, shrubs and grasses (Tanji *et al*., 1993). (Deekshithulu *et al*. 2020) [29, 35] was developed a different irrigation systems calculator using vb6 and also studied yield response of okra to different row spacings and fertilizer application methods under drip irrigation system. At present the trend is towards forage cropping systems (Linneman *et al*., 2014) [14]. On a small scale we see the sequential reuse system put into practice in the Netherlands for crop irrigation in greenhouses (Stanghellini *et al*., 2005) [28].

Importance of Irrigation in Greenhouses

Irrigation is an essential factor of greenhouse cultivation because it directly impacts the growth of the plants. In the greenhouse method of cultivation, the crops depend entirely on the artificial irrigation system for water supply. In the case of open-field cultivation, rainfall also contributes to the moisture of the soil. However, in the greenhouse method of cultivation, crops are provided with proper irrigation schedules to maintain the moisture of the soil at the optimal level.

One of the main advantages of the greenhouse irrigation system is the supply of water exactly according to the requirements of the crops. In the case of the greenhouse method of irrigation, proper irrigation is provided to the crops. It is an essential requirement of the crops to maintain the moisture of the soil. Uniform water supply is provided to the crops by the irrigation system. Uniform water supply is essential for the proper growth of the crops. In the case of the absence of proper water supply, the crops may be adversely impacted. In the greenhouse method of irrigation, the irrigation system plays an important role in the process of fertigation. In the process of fertigation, fertilizers are supplied to the crops. This is especially beneficial in greenhouse cultivation since intensive cultivation of crops requires proper nutrition. Furthermore, efficient irrigation systems help reduce labor costs and improve efficient management of farms. The use of automated irrigation systems also helps improve irrigation efficiency by minimizing human intervention during irrigation. In conclusion, irrigation management is essential in achieving sustainable greenhouse cultivation.

Types of Greenhouse Irrigation Systems

Greenhouse irrigation systems are classified based on method of water application and level of automation.

1. Drip Irrigation System

Fig 1: Drip Irrigation System inside Greenhouse

Drip systems are the most efficient system and offer the greatest degree of control over the amount of water being applied. In addition, since the foliage does not come into contact with water, the potential for disease and injury is reduced. Drip irrigation is useful for the accurate control of moisture levels of the growing medium. It also saves water, labor costs, and the potential for groundwater contamination. Avoid the runoff of water that is not reaching the pot during overhead irrigation systems. The quantity of water being applied to the pot is under the user's control (CUTM, 2020) [22]. Drip Irrigation or Localized Drip Irrigation is a system of irrigation that enables the optimum application of water and fertilizers in protected crops in greenhouses. (Sujatha *et al*. 2023) [34] was worked on a comparative effect of saline water on tomato (lycopersicon esculentummill) crop under drip irrigation. The applied water seeps into the soil or medium and irrigates the area of influence of the roots by a network of tubes (Novagric, 2024) [19].

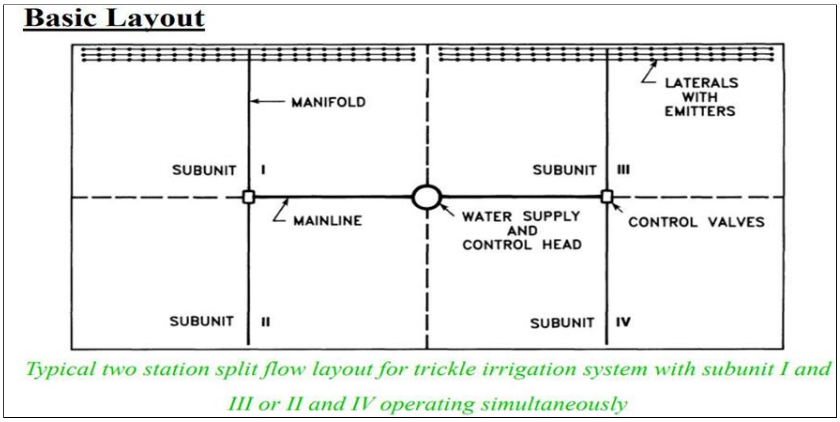
The advantages of using a drip system with nutrient supply in greenhouses

- Makes it easy to distribute fertilizers using the water supply system in a simple and safe manner.
- Saves water and fertilizer.
- Maintains a consistent moisture level in the soil.
- Encourages root growth.
- Saves time (programming of automatic water supply).
- Easy to develop.
- Allows for easy placement of drippers where needed by the plant.
- Increases plant yields (Novagric, 2024) [19].

Disadvantages

- High cost
- Clogging
- Soil Condition (based on infiltration rate)
- Salt accumulation:

Salts tend to accumulate at the surface of the soil and may present apotential hazard since rains may leach salts downward into the root zone.Therefore, when rains follow salt accumulation, irrigation should bemaintained at the normal schedule to leach the salts below the root zone(CUTM, 2020) [4].



Source: Centurion University of Technology and Management, 2020 [4]. Available at: https://courseware.cutm.ac.in/wp-content/uploads/2020/06/LEC-7.PCPHT_.pdf

Fig 2: Basic layout of drip irrigation system

2. Sprinkler Irrigation System

Fig 3: Sprinkler Irrigation System inside Greenhouse

Sprinkler irrigation is a pressurized irrigation system in which irrigation of crops is done by sprinkling water in the form of small droplets, similar to rain. Sprinkler irrigation has a number of advantages over surface irrigation or even over other pressurized irrigation methods such as drip irrigation, since it is not only possible to irrigate the crop but it is also possible to flush the leaves of the crop and control the temperature of the crop canopy to increase the efficiency of the photosynthesis process. A number of research studies have been conducted on sprinkler irrigation, and it has been proved that it is viable and adoptable for economically higher crop production (Xue *et al*., 2016;Liu *et al*., 2011 [15, 31]; Sezen *et al*., 2011; Kiani *et al*., 2022) [10, 25].

Advantages of sprinkler irrigation

- Elimination of the channels for conveyance, therefore, no conveyance loss
- Suitable to all types of soil except heavy clay
- Suitable for irrigating crops where the plant population per unit area is very high. It is most suitable for oil seeds and other cereal and vegetable crops
- Water saving
- Closer control of water application convenient for giving light and frequent irrigation and higher water application efficiency
- Increase in yield
- Mobility of system
- May also be used for undulating area(Sharan, 2002) [26]

Disadvantages of sprinkler irrigation

- Higher capital and operating costs
- Damage to soft fruit plants
- Low efficiency in windy areas
- Inoperability in fields where the soil texture is fine(Ravikumar,2023) [24].

Crop response to sprinkler

The water saving due to sprinkler system compared to conventional method ranged from 16 to 70% with yield improvement from 3 to 57% depending on crops and agro-climatic conditions. (Table.1)

Table 1: Response of different crops to sprinkler irrigation

S. No.	Crops	Water Saving, %	Yield increase, %
1.	Bajra	56	19
2.	Barley	56	16
3.	Bhindi	28	23
4.	Cabbage	40	3
5.	Cauliflower	35	12
6.	Chillies	33	24
7.	Cotton	36	50
8.	Cowpea	19	3
9.	Fenugreek	29	35
10	Garlic	28	6
11	Gram	69	57
12	Groundnut	20	40
13	Jowar	55	34
14	Lucerne	16	27
15	Maize	41	36
16	Onion	33	23
17	Potato	46	4
18	Sunflower	33	20
19	Wheat	35	24

Source : INCID (1998) adapted from Table 6.5

The most common application of automated irrigation scheduling systems is found in the intensive horticultural industry, and in particular the protected cropping industry. Generally speaking, the automated systems used in the industry tend to rely on simple automated timer control, or sometimes even soil moisture sensors to initiate the signal. Where timer control is used, many tend to simply seek to deliver excess water to the point of runoff, although some at least seek to control this by applying sufficient water to meet evaporative demand (Allen *et al*., 1999). A much higher degree of sophistication will be needed if an objective is to improve overall irrigation water use efficiency or to utilize an RDI system. The majority of the remaining automated systems in current operational use are based upon soil moisture sensing, and at least this method has the potential for increased accuracy and water use efficiencies (Jones, 2004) [9].

3. Automated Irrigation Systems

Fig 4 & 5: Automatic Irrigation System inside Greenhouse

Types of automation

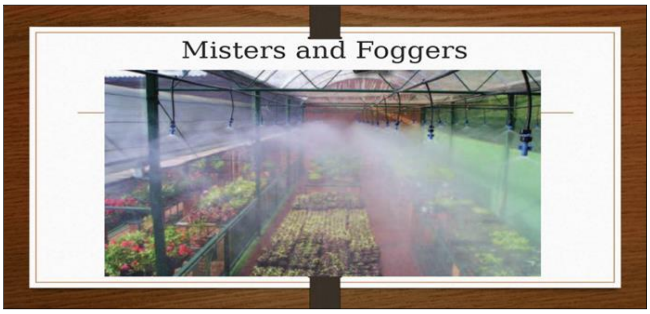
1. Semi-automatic

Semi-automatic systems and controls require manual attention during every irrigation and are often simpler and less expensive than fully automatic systems. Most semi-automatic irrigation systems employ the use of mechanical or electronic timers, which are intended to turn the control structures at specified periods. It is the irrigator who decides when the irrigation should start and for how long, and then manually resets or returns the structures to their original position or from one position to another prior to the next irrigation. Some of the parts of the system can be automatic, while other parts can be semi-automatic or manual. These types of systems make use of communication between the controller and the system's components, which are located in the field(Rathika *et al*., 2020) [22].

2. Fully automatic

Normally, fully automatic systems function without the need to attend to the system except in the case of inspections and maintenance. The irrigator has the option of deciding when and for how long the irrigation is to be done and can turn the water into the system or use programmed controllers to start the automated system. Fully automatic systems can use devices such as tensiometers and electrical resistance blocks to activate the electrical controls when the water in the soil is depleted to a certain level. The duration of the irrigation can be controlled by using a programmed timer, tensiometer, and surface water sensors. Fully automatic systems need a water supply on demand, such as a well and a reservoir, but most farms do not have the flexibility to allow full automation (Rathika *et al*., 2020) [22]

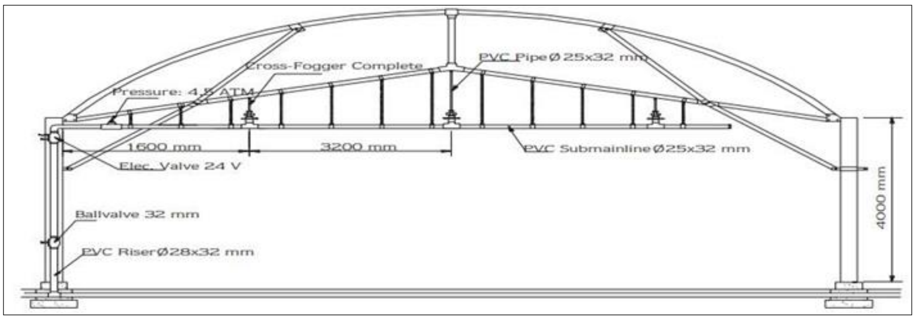
4. Fogging/Misting system



Source: Ravanashre (n.d)

Fig 6: Fogging or Misting system inside Greenhouse,

The FS comprises a water softener and a set of filters that prevent clogging of the nozzles, a water reservoir, pumps and a pressure regulator, and FGNs. The main components of the FS that are included in the PG are presented in Figure 1. The FGNs were uniformly distributed in the PG. The required pressure for FGNs was 4.5 atm. Three nozzle lines, each of which comprises 82 FGN, were installed in the PG spans. At each nozzle line, 82 FGN were uniformly distributed, and the spacing between the nozzles was 2.5 m. The central water feed system was electrically controlled in accordance with the value of the relative humidity (RH) inside the PG(Ozturk,2003) [20]



Source: Ozturk, 2003 [20] adapted from fig1

Fig 7: Plastic greenhouse equipped with the fogging system

Efficiency of the Fogging System

The term "ECE" is generally used to denote saturation efficiency. It is the ratio of the change in saturation achieved to the potential change in saturation. EC systems are generally assessed on the basis of EC or saturation efficiency. It is defined as the ratio of the temperature drop provided by the EC system to the difference between DBT and WBT. WBT is a vital parameter of the ECS. It is the WBT, and not the RH, that determines to what extent air temperature can be reduced by the evaporative cooling of water. Efficiency of the fogging system, denoted by FSE, was found to be determined by the following expression:(Ozturk,2003) [20]

FSE = DBTo - DBTg / DBTo - WBTg x 100

FSE = fogging system efficiency, %

DBTo = dry-bulb temperature outside the greenhouse, °C

DBTg = dry-bulb temperature inside the greenhouse, °C

WBTo = wet-bulb temperature outside the greenhouse, °C

Source: Ozturk,2003 [20]

Table 2: Comparative Analysis of Greenhouse Irrigation Systems

Parameter	Drip Irrigation	Sprinkler Irrigation	Automated Irrigation System	Fogging/Misting System
Mode of Water Application	Water delivered directly to root zone through emitters	Water sprayed over crop canopy	Sensor- and timer-controlled irrigation	Fine droplets sprayed in air for climate control
Water Use Efficiency	Very High	Medium	Very High	Not primary irrigation
Initial Investment	Medium–High	Low–Medium	High	Medium
Labour Requirement	Low	Medium	Very Low	Low
Crop Suitability	Vegetables, fruits, flowers	Nurseries, leafy crops	High-tech greenhouse crops	Seedlings, propagation units
Major Advantages	Saves water, fertigation possible	Easy installation, uniform wetting	Precise control, saves labour	Cooling and humidity control
Main Limitations	Emitter clogging, maintenance	High evaporation, disease risk	High initial cost	Disease risk if overused

Advantages of Greenhouse Irrigation Systems

- Efficient use of water (20-40% water saving) (Nikolaou *et al*., 2019) [18]
- Uniform water distribution in the greenhouse(ARC (2025) [32]).
- Reduces labor requirements
- Helps in stabilizing crop production(Kumar, P. (2024) [12].)
- Controlled environment
- Accurate and uniform application of water

Disadvantages of Greenhouse Irrigation Systems

- System installation is costly (Al-Masaied., 2024) [1]
- Regular monitoring is necessary
- High humidity: risk of fungal diseases (Mahesh Chand Singh *et al*., 2018) [27]
- Cost of additional equipment
- Trained personnel are necessary for operation (FAO Irrigation Guidelines)
- Relies on a reliable water supply

Future Scope

The future of greenhouse irrigation systems would be characterized by precision, automation, and sustainability. The integration of sophisticated soil moisture sensors, climate-based controllers, and decision support tools would allow the farmer to apply the right amount of water depending on the specific needs of the crops at different stages of growth. The use of Internet of Things technologies and remote monitoring tools would also improve the efficiency of the irrigation system. In addition, the use of alternative sources of energy, such as solar power, would reduce the operating costs and the need for the grid as a source of energy. Finally, the development of affordable automation technologies would also allow small and marginal farmers to benefit from the use of sophisticated technologies in managing their irrigation systems. All these developments would improve the sustainability of the greenhouse system.

Future trends in the development of greenhouse irrigation systems may also involve greater integration of crop growth models and the use of artificial intelligence technology to analyze the water status of plants, weather conditions, and soil properties. Such irrigation systems will help farmers make precise irrigation decisions, thus reducing water wastage and enhancing crop yield stability. Closed irrigation systems, which reuse drained water after treatment, may also assume greater importance to conserve water and nutrient resources within a greenhouse. Research is also underway to develop smart emitters and variable-rate irrigation systems, which can control the water flow for different crop areas within a single greenhouse. Such technologies will help improve efficiency and sustain crop production in greenhouses.

Conclusion

Greenhouse irrigation systems are the main pillar of protected cultivation, as it ensures the availability of adequate and timely supply of water for the crops grown in the greenhouse. As rainwater is excluded in the greenhouse, efficient management of irrigation is necessary for maintaining adequate soil moisture for the healthy growth of crops. The use of efficient irrigation methods has a direct impact on the yield, quality, and productivity of the crops grown in the greenhouse. Hence, it is necessary for a person interested in greenhouse cultivation to have a basic knowledge of the principles and applications of different kinds of greenhouse irrigation systems.

Among the different kinds of irrigation methods discussed, drip irrigation and automated irrigation systems have become the most efficient means of modern-day greenhouse cultivation. Sprinkler, fogging, and misting systems also play a vital role in the context of nursery cultivation and regulating the microclimate in the greenhouse. The choice of an efficient irrigation system depends on the nature of the crop, the type of greenhouse, and the availability of resources and expertise in the area of interest.

However, the use of these systems has some challenges, including the initial investment, maintenance, water quality, and the need for a skilled workforce. These challenges need to be addressed in the future in order to encourage the use of advanced irrigation systems in greenhouses. This can be done through proper design, training, and financial incentives. In the future, the use of advanced irrigation systems in greenhouses is expected to be enhanced by the use of precision agriculture technology, automated systems, and environmental sustainability practices. This is because the use of these technologies is likely to reduce the cost of operation and enhance water use efficiency. This is a good sign for the future, and it is expected to contribute to the advancement of sustainable agriculture and food security in the future.

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