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# Drip fertigation in field crops: Effects on productivity, resourceuse efficiency and sustainability

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**Abstract**
Water scarcity and poor nutrient use efficiency have been identified as key limiting factors in agriculture that impact significantly on its productivity and sustainability. The conventional practices of flood and furrow irrigation have low water efficiency and often result in significant losses of both water and nutrients through evaporation, surface runoff, and deep percolation. Therefore, drip irrigation has emerged micro-irrigation techniques, delivering water directly to crop root zone and significantly reducing water losses. In addition to water, the practice of supplying nutrient through irrigation water improves the efficiency of resource utilization by providing the required amounts of nutrients to the crops' active root zone uniformly. Fertigation involves the application of fertilizers in frequent and smaller dosages during various growth stages of crops. It has been shown to improve crop yield, reduce yield variability, enhanced nutrient use efficiency and water use efficiencies (NUE and WUE) respectively, and lower labour costs compared to conventional crop growing methods. Also, the practice is likely to minimize crop cultivation expenses since it resources more efficiently. However, performance is influenced by factors such as soil texture, irrigation frequency, crop type, quality of water used, fertilizers used and their solubility, and water distribution uniformity. This paper gives an insight into the mechanisms involved in drip fertigation systems, fertilizer source, scheduling of fertigation, and the impact of drip fertigation on crop yield, Nitrogen Use Efficiency (NUE), Water Use Efficiency (WUE), and water productivity. It also discusses limitations, technological advances, and future research priorities in the field.

**Keywords:** Drip fertigation, resource efficiency, field crops, nutrient management, water productivity, sustainable agriculture

## 1. Introduction

Increasing population and shrinking cultivable land, need for food, fiber and other commercial crops continues to rise. Important field crops including cereals, pulses, oil seeds, cotton, and sugarcane account for the major share of Indian agricultural products and depend a lot on the availability of water and nutrient supply (Pereira *et al.*, 2002) [26]; (FAO, 2022) [7]; (Kamdi *et al.*, 2024) [19].

Irrigation water and fertilizers have an important role in crop growth, productivity and quality (Locascio, 2005) [23]. Nevertheless, conventional techniques of irrigation and fertilizers application prove to be inefficient as they cause poor usage of inputs, low crop productivity, and ecological consequences related to excessive soil fertility and contamination of groundwater resources (Fageria and Baligar, 2005) [8] ;(Ju *et al.*, 2009) [17].

The consumption of available water resources in agriculture accounts for nearly 70% of the total freshwater resources worldwide, but owing to several factors such as climate change, increasing industrialneeds and rapid urbanization, it becomes more difficult to ensure the sustainability of crop production. In India, the methods of surface irrigation, namely flood irrigation and furrow irrigation, are widely used, however these irrigation methods are relatively inefficient since their efficiency amounts to about 40-60% (Locascio, 2005) [23]; (Pereira *et al.*, 2002) [26]; (Jain *et al.*, 2021) [15].These approaches result in significant water loss via runoff, seepage, evaporation, and deep percolation, leading to the fast depletion of groundwater supplies (Howell, 2001) [14].

Nutrient management is equally important for sustainable productivity. Conventional fertilization leads to nutrient losses resulting from leaching, gaseous emissions, runoff, and fixation (Fageria and Baligar, 2005) [8]; (Ju *et al*., 2009) [17].

The application of fertilizers via irrigation water is referred to as fertigation, which has gained popularity as a technique for managing nutrients and increasing their use and minimizing their loss by delivering fertilizers to the root zone of plants (Bar-Yosef, 1999) [4]. Fertigation is more effective when used in combined with drip irrigation, since fertilizers are delivered in divided doses that coincide with the plant's need for nutrients at various developmental stages (Hebbar *et al*., 2004) [13].

Despite advantages, limitations include high installation cost, clogging, and technical requirements. Recent sensor-based and automated systems have improved efficiency (Nakayama and Bucks, 1991) [24]; (Li *et al*., 2023) [22].

### 2.1 Concept and Principles of Drip Fertigation

Fertigation is the practice of applying water-soluble fertilizers by using the irrigation system through which water and nutrients are applied simultaneously in the root zones of plants. It has the advantage of providing nutrients in a dissolved state thus synchronizing nutrient availability with crop nutrient needs. Of the several ways of implementing the fertigation practice, drip fertigation is very efficient since it provides nutrients accurately in the wetted root zones in appropriate ratios, reducing nutrient losses and fertilizer utilization efficiency. Fertigation works on the principle of delivering dissolved nutrients via irrigation water through the soil profile where the nutrients will be uniformly distributed within the wetted zone as well as maintaining the optimum moisture level around the roots. The frequent application of small amounts of nutrients ensures that there is no build-up of nutrients thus improving the nutrient availability and efficiency of their uptake by plants (Bar-Yosef, 1999) [4]; (Hebbar *et al*., 2004) [13]; (Li *et al*., 2021) [21].

### 2.2 Historical Development of Fertigation

The development of fertigation can be traced back to the development of pressurized irrigation systems and water-soluble fertilizers. The use of fertigation gained significance in greenhouse cultivation in Europe during the 1950s but gained widespread acceptance after the development of drip irrigation in Israel during the 1960s. Improvements in Venturi injectors, fertilizer pump, proportioning injection, and automated controller have increased efficiency in the process. At present, improvements in sensors and computer-based technologies have made fertigation an important technique for applying nutrients to crops (Gebbers and Adamchuk, 2010) [11]; (Goap *et al*., 2018) [12].

### 2.3 Working Mechanism of Drip Fertigation

The fertigation process entails adding high concentrations of fertilizer solution to the pressurized drip irrigation pipeline using a Venturi injector or fertilizer pump. The solution passes through the pipeline system that includes the mainlines, sub-main lines, lateral lines, and emitters. The efficiency of fertigation is dependent on the level of irrigation uniformity, the solubility of the fertilizers, the quality of water used, and the rate of application. Laterals must be flushed after fertigation to prevent emitter clogging from salt deposition and sedimentation (Keller and Bliesner, 1990) [20]; (Bucks *et al*., 1979) [5].

### 2.4 Nutrient Dynamics in the Root Zone

Water application in drip irrigation occurs due to formation of a bulbar wetted zone. Mass flow and diffusion of the nutrients take place, except that nitrate is very mobile and easily moves along with water while phosphorus is less mobile and stays within the wetted zone. Frequent watering in low amounts keeps nutrients within the root zone to prevent deep losses in leaching. With drip fertigation, the roots become established within the wetted zone improving nutrient use and crop performance (Howell, 2001) [14]; (Li *et al*., 2021) [21].

### 2.5 Components of Drip Fertigation System

Drip fertigation is a type of micro-irrigation technology in which fertilizers are supplied through irrigation water to the crop root zone. When used effectively, drip fertigation guarantees that the distribution of water and nutrients in the crops is uniform. A drip fertigation system comprises of a water source, a pumping system, filtration system, fertilizer injectors, the delivery network, emitters, and monitors among others (Keller and Bliesner, 1990) [20]; (Kafkafi and Tarchitzky, 2011) [18]. Prior to setting up a drip irrigation system, it is important to conduct an assessment of irrigation water since drip irrigation systems are susceptible to clogging. Various filtration systems like the media filters, screens, and disk filters need to be installed to eliminatesuspended particles and organic debris from the water. Fertilizers are dissolved in tanks and pumped using the venturis or injectors to ensure their delivery while pipeline delivery systems ensure the even pressure across the fields. Emitters release the water and nutrients at desired amounts while pressure gauges, and EC/pH meters ensure the maintenance of the system (Bao *et al*.,2023) [3]; (Gebbers and Adamchuk, 2010) [11]; (Li *et al*., 2023) [21].

### 2.6 Fertilizers Suitable for Drip Fertigation

Drip fertigation efficiency relies on using fertilizer materials that are highly water-soluble, stable, and compatible with the quality of irrigation water. The fertilizers need to dissolve fully to avoid precipitation and clogging of the drip emitters. The nitrogen fertilizers used include urea and calcium nitrate because of their mobility and quick response by crops. Phosphate fertilizers include mono-ammonium phosphate and phosphoric acid because of their high solubility, while the most common potash fertilizers include potassium nitrate and potassium sulphate. It is important for fertilizers to be compatible since the calcium fertilizers cannot mix with phosphate and sulphate fertilizers because of precipitation causing clogging (Bucks *et al*., 1979) [5]; (Kafkafi and Tarchitzky, 2011) [18]

### 2.7 Fertigation Scheduling and Application Methods

The fertigation scheduling is defined as the fertilizers applied in the soil through irrigation water based on the plant nutrient needs during different growth phases. Fertigation scheduling increases NUE and WUE because it ensures that nutrients are present in the active root zone without causing any losses. The sandy soils require more frequent fertigation since due to their high leaching tendency.In contrast, clay soils allow irrigation for longerdurations owing to their water holding capacity.

Several commonly used fertigation methods include continuous, proportional, quantitative, and split fertigation, with the latter being appropriate for field crops. The recent advancement in technology has enhanced the efficacy of fertigation (Jones, 2004) [16]; (Li *et al*., 2023) [21].

### 2.8 Effect of Drip Fertigation on Crop Yield and Quality

Drip fertigation enhances the crop production rate by supplying continuous nutrition and water to the plant root system. The continuous application of minute amounts of nutrients prevents the leaching process and sustains high concentration of nutrient in the soil solution. This leads to stability in both crop yield and quality. Significant yield improvements in annual crops have been reported globally through the adoption of drip fertigation practices(Ayars *et al*., 1999) [2]; (Delbaz *et al*., 2023) [6]; (Li *et al*., 2021) [21]; (Vaddula and Singh, 2023) [33].

### 2.9 Effect on Water Use Efficiency (WUE) and crop water Productivity (CWP)

Water use efficiency is said to be the output of the product in relation to the quality of water applied and the amount actually consumed by the crop. The drip irrigation process brings about increased WUE because it directs the water flow to the root area, preventing loss of water through the process of evaporation, run-off, and leakage. Soil moisture availability will contribute to better growth in the roots system and physiology of plants, thus leading to higher efficiency in terms of water usage, especially in areas that lack water. Modern studies have further advocated for the importance of weather-based irrigation scheduling for the use of drip irrigation (Howell, 2001) [14]; (Pereira *et al*., 2002) [26]; (Li *et al*., 2021) [21]

### 2.10 Effect on Nutrient Use Efficiency (NUE)

Nutrient use efficiency is described as the capacity of the plants to extract and efficiently make use of the applied nutrients. Traditional techniques of fertilizer application led to the loss of nutrients through processes such as leaching, volatilization, runoff, and fixation. Fertigation through a drip irrigation system maximizes NUE since the nutrient inputs are applied directly into the root zone with wet soil in smaller split dosages, thus maximizing the nutrient recovery rate. This ensures that nutrient inputs and crop needs are synchronized, leadingto higher fertilizer recovery efficiency, particularly when nitrogen fertilizers are applied Sensor-based fertigation technologies have further improved NUE by optimizing nutrient delivery based on real-time field conditions (Bar-Yosef, 1999) [4]; (Jain *et al*., 2021) [15]; (Li *et al*., 2021) [21]

### 2.11 Soil Health, Environmental Impact and Sustainability

Drip fertilization promotes environmental sustainability through minimizing the mobility of nutrients past the root zone. Controlled application of nutrients promotes reduced nitrate leaching into the ground and hence reduces pollution of underground water sources. Runoff is minimized, thus preventing the occurrence of water eutrophication. Evenness in moisture and nutrients could stimulate activities of microorganisms within the soil. Consequently, drip fertilization can be cited as an essential technology for soil enrichment and sustainable agricultural systems (Zhang *et al*., 1996) [34]; (Ju *et al*., 2009) [17].

### 2.12 Economic Feasibility of Drip Fertigation

In drip fertigation, higher upfront cost will be incurred due to the installation of the pumps, filtration system, laterals, emitters, and fertigation unit. Nevertheless, long-term advantages such as increased production levels, enhanced product quality, less loss of fertilizers, and efficient use of water and labour can be realized. The economic feasibility depends on crop value, farm size, and availability of technical support (FAO, 2022) [7]; (Sidhu *et al.*, 2019) [28].

### 2.13 Salinity and Water Quality Management

Water quality has an extremely significant bearing on the success of the method of drip fertilizer application. High salinity affects nutrient availability and plant growth, while high pH and bicarbonates could lead to precipitation and blockage. Water flushing, filtration, and control of electrical conductivity should be considered. Salinity is among the major factors discussed in literature with great emphasis laid on its significance for drip fertilization (Frenkel, 1984) [9]; (Frenkel *et al*., 1980) [10].

### 2.14 Recent Advances in Fertigation Technology

New advancements have come in the form of automatic fertilization devices, incorporation of soil moisture sensors, scheduling based on evapotranspiration, and internet of things (IoT)-based smart fertigation devices. With the help of such advanced technology, crops can be monitored effectively, leading to improved crop performance and lower losses (Goap *et al*., 2018) [12]; (Bao *et al*., 2023) [3]; (Li *et al*., 2023) [22].

### 2.15 Limitations and Constraints

Some of the major limitations are the high installation cost, clogging problems, need for technical expertise, and dependance on water quality. Maintenance and filtering along with regular flushing is necessary for maintaining the performance of the system (Bucks *et al*., 1979) [5]; (Nakayama and Bucks, 1991) [24].

### 2.16 Research Gaps and Future Research Priorities

Further scientific studies are required regarding the impact of fertigation on soil fertility and carbon dynamics, scheduling models crop-specifically, as well as integration of real-time sensor and automation technology. Moreover, low-cost fertigation systems have to be invented that can be adopted by small scale farmers (Li *et al.*, 2021) [21]; (Rana *et al*., 2023) [27]; (Subramanian *et al*., 2023) [31].

### 2.17 Critical Considerations and Practical Challenges in Field Conditions

Field performance of drip fertigation depends on soil type, irrigation scheduling, water quality, and farmer management. The sandy soil requires frequent low volume irrigations to reduce nutrient leaching. Clayey soil is highly susceptible to flooding because of excess irrigation. The pressure differences, emitter blockage, and uneven nutrient delivery may result in non-uniformity. Appropriate choice of fertilizers, compatibility tests, and filtration are vital in making the process effective. The technology has not been widely adopted for field crops because of the high costs incurred; thus, development of low-cost systems is important for wider adoption.

## 3. Conclusion

Fertigation through drip is seen to be an environmentally friendly and resource-conservative method to increase crop production and achieve efficient use of water and nutrients. The literature review reveals that fertigation is highly beneficial in terms of increasing the yield output by allowing simultaneous supply of nutrients and water to the roots through drip, thus avoiding their losses. Other than providing agronomic advantages, fertigation also ensures environmental sustainability by preventing nutrient leakage, groundwater pollution, and efficient utilization of resources despite limited availability of water resources. Fertigation, however, remains constrained by economic barriers, technical ignorance, and other problems during the implementation of the technique. Thus, policy makers, along with farmers themselves, should promote the technology in order to ensure its widespread adoption.

## Tables

**Table 1:** Yield response of major field crops under drip fertigation (evidence-based synthesis)

| S. No. | Crop | Yield improvement (%) | Evidence type | Key agronomic mechanism | Supporting studies |
|---|---|---|---|---|---|
| 1 | Maize | 15–35 | Meta-analysis + field trials | Improved N synchrony + root-zone moisture stability | Li *et al.* (2021) [21]; Singh *et al.* (2024) [29,30] |
| 2 | Wheat | 10–25 | Field experiments | Better nutrient partitioning + reduced leaching | Pereira *et al.* (2002) [26]; Kamdi *et al.* (2024) [19] |
| 3 | Rice (aerobic/drip) | 15–30 | Controlled trials | Root-zone aeration + regulated irrigation | Subramanian *et al.* (2023) [31] |
| 4 | Cotton | 20–35 | Multi-location field studies | Improved boll retention + fertigation efficiency | Vaddula and Singh (2023) [33] |
| 5 | Peanut | 10–20 | Field experiments | Enhanced pod filling + moisture uniformity | Jain *et al.* (2021) [15] |
| 6 | Cassava | 12–25 | Regional trials | Improved tuber bulking under regulated water | Sunitha *et al.* (2016) [32] |

**Note:** The percentages indicated for yield enhancement (%) are ranges developed from scientific field studies and meta-analyses carried out under varied agronomic and climatic environments, soil types, and fertigation systems. The variations observed may be due to the following factors: cultivar, timing of irrigation, type of fertilizers used and their concentration, soil textures, and system design.

**Table 2:** Water saving and improvement in water use efficiency (WUE) under drip fertigation system

| S. No. | Crop system | Water saving (%) | WUE improvement (%) | Experimental basis | Supporting studies |
|---|---|---|---|---|---|
| 1 | Maize/Wheat systems | 30–50 | 25–60 | Irrigation scheduling trials | Howell (2001) [14]; Li *et al.* (2021) [21] |
| 2 | Rice (drip/aerobic) | 20–40 | 30–55 | Field lysimeter + ET-based studies | Subramanian *et al.* (2023) [31] |
| 3 | Cotton | 40–60 | 35–70 | Multi-season field validation | Vaddula and Singh (2023) [33] |
| 4 | Vegetables | 30–50 | 40–80 | High-frequency fertigation trials | Locascio (2005) [23] |
| 5 | Pulses | 20–40 | 25–50 | Soil-moisture controlled experiments | Jain *et al.* (2021) [15] |

**Note:** The figures for water saving (%) and improvement in water use efficiency (%) have been derived through controlled experiments conducted in the fields, lysimeters, and experiments related to irrigation scheduling using evapotranspiration. Factors influencing variability in the findings include the climatic demand (evapotranspiration), design of irrigation methods, crop types, characteristics of soil hydraulic properties, and application frequency of fertilizers.

**Table 3:** Comparison of conventional fertilization and drip fertigation

| Parameter | Conventional system | Drip fertigation | Improvement mechanism | Evidence base |
|---|---|---|---|---|
| Nitrogen use efficiency (NUE) | 30–50% | 60–90% | Split application + reduced leaching | Bar-Yosef (1999) [4]; Fageria and Baligar (2005) [8] |
| Water use efficiency (WUE) | Low–moderate | High | Root-zone water delivery | Howell (2001) [14] |
| Nutrient loss | High | Low | Reduced runoff & percolation | Ju *et al.* (2009) [17] |
| Yield stability | Variable | Stable | Reduced stress fluctuation | Li *et al.* (2021) [21] |
| Labour requirement | High | Low | Automation + fertigation units | Goap *et al.* (2018) [12] |
| Fertilizer requirement | High | 15–30% lower | Higher uptake efficiency | Sidhu *et al.* (2019) [28] |
| Environmental impact | Negative | Positive | Reduced nitrate pollution | Zhang *et al.* (1996) [34] |

**Note:** Values of comparative efficiency of conventional fertilizers application and drip fertigation are taken from peer-reviewed scientific research articles, reviews, and other sources. Higher efficiency of fertilizer and water application, better yield stability, and reduced environmental load depend on a number of factors such as soil fertility, crops grown, irrigation practices, and methods for fertilizer application. Comparison is based on observations made across a wide range of agro-ecosystems.

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