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Drip fertigation in modern agriculture: A key strategy for efficient nutrient and water management

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ABSTRACT

Drip fertigation combines the application of irrigation water and soluble fertilizers through a drip system, facilitating the supply of water and nutrients directly to the crop root zone in accordance with crop requirements. Its ability to provide nutrients in small, frequent and localized applications allows closer synchronization between nutrient supply, crop demand and soil moisture conditions. The increasing demand for efficient use of water and fertilizers has positioned drip fertigation as an important component of precision and sustainable crop production. This review summarizes the current understanding of drip fertigation with particular emphasis on different crops. The review examines the influence of fertigation on crop growth, yield and yield components, produce quality, nutrient uptake and nutrient-use efficiency, water-use efficiency, and nutrient distribution in the root zone. Published evidence indicates that precise and frequent application of water and nutrients can improve synchronisation between nutrient supply and crop demand, thereby enhancing nutrient uptake and productivity while reducing unnecessary water and fertilizer losses. A meta-analysis reported that drip fertigation increased crop yield, water productivity and nitrogen-use efficiency by 12.0, 26.4 and 34.3%, respectively, compared with conventional irrigation and fertilizer practices. Vegetable-focused evidence also indicates improvements in yield, water-use efficiency, nitrogen productivity and quality, although responses vary with crop type, irrigation amount, nitrogen rate, soil conditions and cultivation environment. The review further discusses fertigation scheduling, fertilizer concentration, application frequency, root-zone nutrient dynamics, economic considerations and constraints such as initial investment, emitter clogging and improper nutrient management. Overall, drip fertigation provides an effective pathway for integrating water and nutrient management and offers considerable potential for improving productivity, resource-use efficiency and sustainability in crop production.

Keywords: Drip fertigation, Nutrient-use efficiency, Nutrient management, Water-use efficiency, Crop productivity, Root-zone nutrient dynamics, Sustainable agriculture

1. Introduction

Availability of Freshwater is a prime requirement for the agriculture sector, but increasing demand for food production, domestic use and the industrial sector has intensified the need for efficient irrigation (Verma *et al.*, 2025) [1]. Agriculture accounts for a very large share of freshwater use in India and emphasises the growing relevance of micro-irrigation, irrigation scheduling and resource conservation practices. Between 2009–10 and 2019–20, the reported area under micro-irrigation increased from 9.39 to 15.91 Mha, indicating a substantial shift toward water-efficient technologies, although the area remains small relative to total irrigated land. (Shi *et al.*, 2022) [2].

Nutrient losses like leaching, runoff, volatilization, denitrification and other soil processes further complicate agricultural resource management. Losses are particularly important when fertilizer application is poorly synchronized with crop demand or when large quantities are exposed to irrigation or rainfall. Fertigation addresses these limitations by delivering nutrients with irrigation water, allowing the timing, frequency and concentration of nutrient supply to be adjusted to crop growth and soil conditions (Parihar *et al.*, 2019) [3].

The scientific basis of fertigation lies in matching nutrient supply with water distribution. Instead of applying a large fertilizer dose at one time, nutrients can be supplied in smaller quantities and delivered repeatedly through the irrigation system. This ensures nutrients are readily available in the root zone, and the major advantage of fertigation is synchronisation. Nutrient availability can be ensured in accordance with crop phenological stage, while irrigation can be adjusted to soil moisture demand. When these two streams are coordinated, nutrient concentration in the active root zone can be maintained closer to the level required for plant uptake.

Gireesh *et al.* (2020) [4] evaluated different irrigation and fertilizer levels under drip irrigation in chilli (*Capsicum annuum*). Results showed that application of 80% irrigation water requirement with recommended fertilizer dose of 200 kg ha⁻¹ N, 125 kg ha⁻¹ P and 125 kg ha⁻¹ K produced 24.80 t ha⁻¹ yield and a

fertilizer-use efficiency of 55.1 kg kg⁻¹ N. The study also showed that increasing fertilizer and irrigation beyond optimum levels did not provide additional benefits, demonstrating the importance of synchronising nutrient requirement and water supply.

2. Concept and principle of fertigation

Fertigation is the controlled application of fertilizer through irrigation water (Hagin *et al.*, 2002) [5]. In practical systems, fertilizer is dissolved in irrigation water and injected into the pressurised irrigation network so that the nutrient solution reaches the crop through emitters or sprinklers. The process links three management decisions on how much nutrient is required, when it is required, and where it should be delivered (Sandal *et al.*, 2015) [6].

Fertigation enables precise, timely application of soluble fertilisers according to crop demand and growth stage. When combined with drip irrigation, it improves water and nutrient-use efficiency, enhances crop productivity and reduces nutrient losses through leaching. Frequent application of small fertilizer doses is particularly beneficial in light-textured soils, where nutrients are prone to movement below the root zone (Ashrafi *et al.*, 2020) [7].

3. Fertigation system and major components

Fertigation equipment is designed to deliver fertilizers accurately along with irrigation water to crops. The core components include:

Water source and pumping unit

The system begins with a well or water source that supplies irrigation water. A pump lifts and pressurises the water so it can flow through the filtration, fertigation and distribution network. A bypass valve is provided to regulate or divert water flow around the pumping unit when required.

Sand separator/hydro-cyclone

The sand separator or hydro-cyclone removes heavier particles such as sand and grit from the irrigation water before it enters the filtration system. This protects downstream components and reduces the possibility of clogging.

Filtration unit

The sand filter removes relatively fine suspended particles and organic matter, while the screen filter provides additional filtration before water enters the distribution network. The backwash valve allows accumulated impurities to be removed from the sand filter.

Pressure gauge and pressure control

The pressure gauge is used to monitor the operating pressure of the irrigation system. Maintaining appropriate pressure is essential for achieving uniform water and fertilizer distribution through the drippers.

Fertilizer injection unit

A Venturi injector is used for injecting soluble fertilizer into the irrigation water. The pressure difference created across the Venturi causes the fertilizer solution to be drawn into the irrigation pipeline. This allows nutrients to be transported with irrigation water directly to the crop root zone.

Non-return valve (NRV)

Non-return valves (NRVs) prevent the reverse flow of water or fertilizer solution. They protect the pump and prevent contaminated or fertiliser-enriched water from flowing back toward the water source.

Mainline

The mainline is the primary pipeline that carries filtered and fertilized water from the filtration or fertilizer injection unit to different parts of the field. It forms the main pathway for water distribution.

Sub-main line

The sub-main line receives water from the mainline and distributes it to individual field sections or groups of laterals. Ball valves are used to control the flow to different sections, allowing individual areas to be irrigated separately.

Polytube/laterals

The polytube or lateral lines are smaller pipes laid along the crop rows. They transport the water–fertilizer mixture close to individual plants root zone. Several laterals can be connected to a single sub-main line.

Drippers/emitters

Drippers or emitters are the final delivery points of the system. They release water and dissolved nutrients at a controlled and low discharge rate near the plant root zone. This minimizes water losses and improves the efficiency of nutrient application.

Flush valves and end stops

Flush valves are provided at the ends of laterals and other pipeline sections to remove accumulated sediments and impurities. End stops close the ends of lateral lines and help maintain proper water pressure within the system.

Air valve

The air valve releases trapped air from the pipeline and allows air to enter when necessary during system drainage. Proper air management helps prevent pressure fluctuations and pipeline-related problems.

Ball valves

Ball valves regulate the flow of water to different sections of the field. They allow the operator to open or close individual irrigation zones according to crop and field requirements.

3.1 Fertigation versus conventional fertilisation

Parameter	Conventional soil application	Fertigation
Placement	Broadcasting, banding or manual placement	Nutrients are delivered with irrigation water
Timing	Limited number of applications with higher doses of fertilizers	Frequent applications with lower doses of nutrients
Distribution	Depends strongly on soil movement and irrigation pattern	Follows the wetted irrigation zone
Labour	Relatively high for repeated applications	Reduced after system installation
Leaching risk	Can increase after huge quantity application of a time	Can be reduced through smaller doses and frequent application
Precision	Lower	Higher when flow and concentration are controlled

Drip fertigation enables precise and frequent nutrient application, improving nutrient availability and uptake while reducing labour and nutrient losses. Compared with conventional fertilization, it promotes

better fertilizer-use efficiency, water productivity and crop performance through synchronized water and nutrient delivery (Li *et al.*, 2021) [9].

4. Methods of fertigation

According to Ashrafi *et al.* (2020) [7], for the application of the same doses of fertilizers during the specific phenological stage of a plant, two different mechanisms of application can be used depending on

the crop, soil type and farm management system:

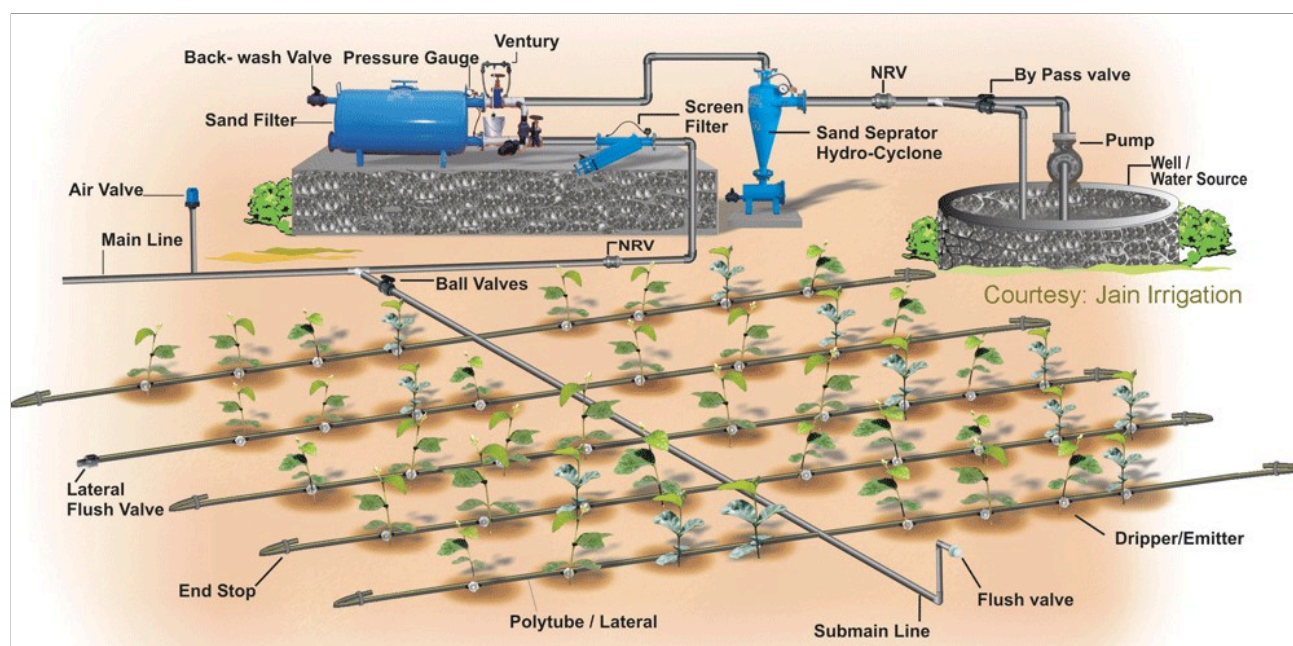


Figure 1. Schematic representation of a fertigation system and distribution of fertilizer through irrigation water
Source: Jain Irrigation, as reproduced in Infonet Biovision (2020) [8], *Water for irrigation*.

4.1 Quantitative fertigation

A measured amount of fertilizer is injected into the irrigation system in the time of each water application. Injection may be initiated and controlled automatically as well as manually. This method is mostly used in soil.

4.2 Proportional fertigation

Proportional fertigation maintains a defined ratio between fertilizer solution and irrigation water. It is particularly useful where a relatively constant nutrient concentration is required in the irrigation

stream. This method is commonly used in the soilless media and sandy soils.

4.3 Split application

Splitting the total fertilizer requirement into multiple applications is a central fertigation strategy. Khanna *et al.* (2018) [11] divided fertilizer application into eight equal splits in maize and reported placement close to the plant base, helping to minimize leaching and improve nutrient utilization.

Table 1. Fertiliser use efficiency under different methods of fertiliser application (%)

Nutrient	Soil application (%)	Drip + soil application (%)	Drip + fertigation (%)
N	30–50	65	95
P ₂ O ₅	20	30	45
K ₂ O	60	60	80

(Source: Biswas, 2010) [10]

The choice between quantitative and proportional fertigation depends on soil texture, crop demand, irrigation frequency, system capacity and the desired nutrient concentration. In precision farming, the most appropriate approach is one that delivers the required nutrient dose while maintaining hydraulic uniformity and minimizing nutrient movement beyond the active root zone.

5. Fertilizer injection technologies

Fertilizer injection technology is an important component of fertigation systems because it determines the rate, concentration and uniformity with which dissolved nutrients are introduced into irrigation water. The major fertilizer injection methods used in pressurized irrigation systems include Venturi injectors, pressure-differential fertilizer tanks, and pump-based injection systems (Fan *et al.*, 2017; Omary *et al.*, 2020) [12, 13].

5.1 Pressure differential or bypass tank

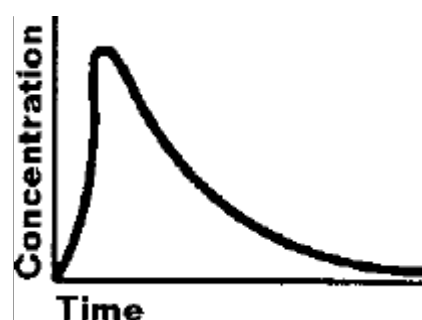


Figure 2. Typical fertilizer concentration pattern associated with pressure-differential injection.

(Source: Adapted from Çetin and Akalp (2019) [14].

The pressure differential system creates a pressure difference across the fertilizer tank so that irrigation water enters and exits the tank carrying dissolved fertilizer. This system is simple and suitable for perennial crops, but notes that fertilizer concentration declines as the tank is depleted. Consequently, application uniformity and quantitative accuracy can be limited.

5.2 Venturi injection

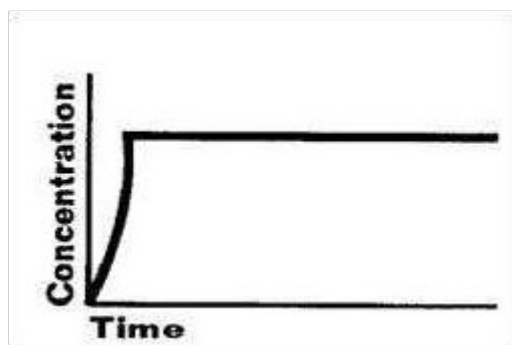


Figure 3. Typical fertilizer concentration pattern for a controlled injection process.

Venturi injection uses a pressure differential generated by a constricted section of pipe to create suction and draw fertilizer solution into the irrigation stream. It has few moving parts and is relatively simple to install. However, pressure loss across the injector and sensitivity to hydraulic conditions can affect injection consistency.

5.3 Pump injection

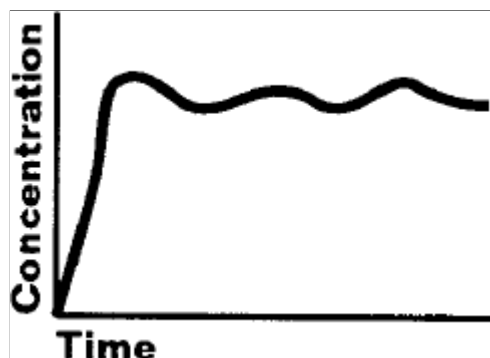


Figure 4. Representative fertilizer concentration pattern illustrating controlled injection. .
(Source: Adapted from Çetin and Akalp (2019) [14].

Pump injection uses an electric or hydraulic pump to introduce fertilizer solution into the irrigation mainline. It is more suitable for accurate proportional fertigation and automation but generally has higher capital and maintenance requirements than simple pressure differential systems.

6. Emitters, filtration and distribution uniformity

Emitters determine how irrigation water and dissolved nutrients are released to the crop. Different types of emitters: inline emitters, on-line emitters, pressure-compensating emitters, non-pressure-compensating emitters, adjustable-flow emitters, flag emitters and microtubes (Zhangzhong *et al.*, 2015) [15].

1. Inline (inbuilt) emitters

Inline emitters are manufactured or inserted inside the dripline at pre-determined intervals and are therefore suitable where plants are arranged in regular rows and uniform spacing is required. They are widely used in vegetable and row-crop production because the emitter spacing can be selected according to crop geometry. Their perfor-

mance depends on operating pressure, emitter design and the hydraulic characteristics of the lateral. (Source: Sokol *et al.*, 2022) [16].

2. Online emitters

Online emitters are installed externally on a plain lateral, allowing the emitter position to be selected according to individual plant locations. This makes them particularly useful for orchards, plantations and crops with irregular plant spacing. Their flexibility also allows the number and location of emitters to be modified according to changing crop water requirements.

3. Pressure-compensating (PC) emitters

Pressure-compensating emitters are designed to maintain a relatively constant discharge despite variations in operating pressure. A flexible diaphragm or regulating mechanism adjusts the flow through the emitter, thereby improving discharge uniformity along the lateral. Consequently, PC emitters are particularly useful in long laterals, sloping or uneven fields, and systems where pressure variation is significant. Recent research confirms that PC emitters can improve irrigation uniformity, although their compensation mechanism can be affected by clogging and deterioration under adverse water-quality conditions.

4. Non-pressure-compensating emitters

In non-pressure-compensating emitters, discharge varies with the pressure available at the emitter. Therefore, emitters located at different positions along a lateral may have different discharge rates when pressure losses occur. They are generally simpler in construction and can be economical for short laterals and relatively level fields, where pressure variation is limited. Research on emitter hydraulics has demonstrated the importance of the pressure–discharge relationship in determining the uniformity of non-PC emitters.

5. Adjustable-flow emitters

Adjustable-flow emitters allow the discharge rate to be modified manually according to the water requirement of individual plants. This characteristic provides flexibility where plants have different water requirements or where irrigation needs change during crop development. Such emitters can also be adjusted or closed when irrigation is not required at a particular location. Their suitability is therefore greater in systems requiring individualized water management.

6. Flag emitters

Flag emitters are a type of online emitter designed to facilitate flushing and cleaning of the flow path. Their removable or accessible design can make maintenance easier where clogging is a concern. They can be useful in orchards, nurseries and other applications where individual emitters are installed according to plant position. However, their performance still depends on irrigation-water quality, filtration and regular maintenance because all drip emitters have relatively small flow passages that are susceptible to clogging.

7. Microtubes

Microtubes are simple small-diameter tubes used to deliver water or fertigation solution directly to individual plants. Their discharge can be regulated by changing the tube diameter, length and hydraulic characteristics. Microtube systems are useful where a simple and inexpensive point-delivery arrangement is required and can be integrated with lateral lines or other emitter arrangements. Their hydraulic performance, however, needs to be properly designed to obtain the desired discharge and uniformity.

Operational implication

Regular filter cleaning, monitoring of emitter discharge, maintenance of appropriate pressure and periodic system flushing are essential. Where water quality is poor, filtration and chemical treatment should be selected according to the nature of suspended and dissolved contaminants.

	(1) INLINE EMITTERS (Inbuilt)	(2) ONLINE EMITTERS	(3) PRESSURE- COMPENSATING EMITTERS (PC)	(4) NON-PRESSURE- COMPENSATING EMITTERS (Non-PC)	(5) ADJUSTABLE FLOW EMITTERS	(6) FLAG EMITTERS	(7) MICROTUBES
Appearance (External)							
Cross section / Internal structure	 Emitter built in the dripline	 Emitter inserted on the lateral	 Flexible diaphragm maintains constant flow over a range of pressures	 Flow varies directly with pressure changes	 Flow rate can be increased (+) or decreased (-) or shut off	 Flag opens for flushing/cleaning, resistant to clogging	 Small tube delivers water directly to the plant
Key features / Use	Inbuilt in dripline at regular intervals; suitable for uniform row crops and close spacing.	Installed externally at desired points; suitable for trees, orchards and irregular spacing.	Maintains nearly constant discharge despite pressure variations; suitable for long laterals and uneven terrain.	Discharge varies with pressure; economical; suitable for short laterals on level fields.	User can adjust flow rate as per crop water requirement; can be turned off.	Easy to open and flush; good clog resistance; suitable for poor quality water.	Small diameter tubes; flow depends on length and diameter; delivers water directly to the root zone.

Plate 1. Types of drip emittersSource: Sokol *et al.* (2022) [16]

7. Fertilizer selection for fertigation

Fertilizers used in fertigation should dissolve rapidly and completely under field conditions. It should contain minimal insoluble material and remain chemically compatible with other fertilizers and irrigation water. Fertilizers with high nutrient concentration, rapid dissolution,

low residue, and rapidly available to plants can be used for fertigation.

1. Fertilizers suitable for fertigation

Some of the common Nitrogen, Phosphorus, and Potassium fertilisers suitable for fertigation are listed in the table.

Table 2. Water-soluble fertilisers (Ashrafi *et al.*, 2020) [7]

Nutrient	Water-soluble fertilisers	Nutrient content
Nitrogen	Urea	46-0-0
	Ammonium Nitrate	34-0-0
	Ammonium Sulphate	21-0-0
	Calcium Nitrate	16-0-0
	Magnesium Nitrate	11-0-0
	Urea Ammonium Nitrate	32-0-0
	Potassium Nitrate Monoammonium Phosphate	13-0-46
Phosphorus		32-0-0
	Monoammonium Phosphate	12-61-0
	Monopotassium Phosphate	0-54-32
	Phosphoric Acid	0-82-0
Potassium	Potassium Chloride	0-0-60
	Potassium Sulphate	0-0-50
	Potassium Nitrate PotassiumThiosulphate	13-0-46
		0-0-25
		0-52-34
Micronutrients	Fe EDTA	13 (Fe)
	Fe DTPA	12 (Fe)
	Fe EDDHA	6 (Fe)
	Zn EDTA	15 (Zn)
	Ca EDTA	9.7 (Cu)

8. Fertilizer compatibility and precipitation

Chemical compatibility is one of the most important safeguards against emitter clogging. Precipitation may occur when incompatible fertilizer salts react in concentrated stock solutions or in irrigation water. Avoid mixing calcium nitrate with phosphate or sulphate fertilizers, magnesium sulphate with mono- or diammonium phosphate, and phosphoric acid with sulphates of iron, zinc, copper and manganese.

8.1 Compatibility management

In fertigation systems, fertilizer compatibility management is essential to prevent precipitation, clogging of filters and emitters, and uneven nutrient distribution. Fertilizers that are chemically incompatible should be prepared in separate stock solutions, and their compatibility should be tested using the actual irrigation water before field application. The pH and chemical composition of irrigation water, particularly the concentrations of calcium, magnesium, bicarbonate and iron,

should be considered because these ions may react with fertilizer components and form insoluble precipitates. Excessive fertilizer concentrations in the stock solution should also be avoided, and the irrigation system should be flushed after fertigation to remove residual

fertilizer and minimise the accumulation of precipitates within pipelines and emitters. Effective compatibility management therefore helps maintain system performance, nutrient availability and uniform fertilizer application in precision fertigation.

Table 3. Common Fertilizer Incompatibilities in Drip Fertigation and Their Causes

Fertilizer	Should not be mixed with	Reason
Calcium nitrate	Any phosphates or sulphates	Precipitation of insoluble calcium phosphate/sulphate
Magnesium sulphate	Di- or mono-ammonium phosphate	Formation of insoluble magnesium phosphate precipitate
Phosphoric acid	Iron, zinc, copper & manganese sulphates	Precipitation of metal phosphate compounds, clogging emitters

	Urea	Ammonium nitrate	Ammonium sulfate	Calcium nitrate	Potassium nitrate	Potassium chloride	Potassium sulfate	Ammonium phosphate	Fe, Zn, Cu, Mn sulfate	Fe, Zn, Cu, Mn chelate	Magnesium sulfate	Phosphoric acid	Sulfuric acid	Nitric acid
Urea	√													
Ammonium nitrate	√	√												
Ammonium sulfate	√	√	√											
Calcium nitrate	√	√	X	√										
Potassium nitrate	√	√	√	√	√									
Potassium chloride	√	√	√	√	√	√								
Potassium sulfate	√	√	R	X	√	R	√							
Ammonium phosphate	√	√	√	X	√	√	√	√						
Fe, Zn, Cu, Mn sulfate	√	√	√	X	√	√	R	X	√					
Fe, Zn, Cu, Mn chelate	√	√	√	R	√	√	R	√	√	√				
Magnesium sulfate	√	√	√	X	√	√	R	X	√	√	√			
Phosphoric acid	√	√	√	X	√	√	√	√	√	R	√	√		
Sulfuric acid	√	√	√	X	√	√	R	√	√	√	√	√	√	
Nitric acid	√	√	√	√	√	√	√	√	√	X	√	√	√	√

√ = compatible X = incompatible R = reduced compatibility

Figure 5. Fertilizer compatibility relationships relevant to fertigation (Roddy, 2006) [17].

9. Fertigation scheduling

Fertigation scheduling refers to determining the appropriate quantity, concentration, timing and frequency of nutrient application according to crop and field requirements. Proper scheduling improves nutrient-use efficiency, minimizes nutrient losses and ensures that nutrients are supplied according to crop demand. The major factors influencing fertigation scheduling include crop growth stage, site-specific nutrient requirements, irrigation requirements, irrigation-water pH and electrical conductivity (EC). Crop stage determines the changing nutrient demand throughout the growing period, while site-specific soil and crop requirements help determine the appropriate nutrient dose. Irrigation requirements influence the timing and duration of fertigation, whereas pH and EC are important for maintaining nutrient availability and avoiding excessive salt accumulation in the root zone. Therefore, integrating these factors is essential for achieving efficient and uniform nutrient application under precision fertigation (Singh *et al.*, 2026) [18]. Top of Form Bottom of Form Fertigation Scheduling provides flexibility in both nutrient quantity and frequency. Fertigation events may be weekly, fortnightly or monthly depending on crop and system, but high-frequency applications are often useful

where soluble nutrients are vulnerable to leaching (Thompson *et al.*, 2003) [19].

Amala *et al.* (2016) [20] evaluated 75, 100, 125 and 150% of the recommended N and K through fertigation with intervals of four and eight days. The 125% level recorded 33.67 fruits plant⁻¹ and 42.36 t ha⁻¹, while the four-day interval produced 35.53 fruits plant⁻¹ and 44.25 t ha⁻¹. These results demonstrate that increasing the fertilizer dose alone does not define the optimum schedule; frequency and synchronization with crop demand are equally important. Ughade *et al.* (2018) [21] evaluated different fertigation levels and schedules in tomato under naturally ventilated poly house conditions. The study compared 60, 80 and 100% of the recommended dose of fertilizer with fertigation schedules involving 6 splits at 18-day intervals, 9 splits at 12-day intervals and 12 splits at 9-day intervals. Application of 80% RDF in 12 equal splits at 9-day intervals up to 120 days after transplanting produced higher fruit yield and economic returns, demonstrating the importance of adjusting fertigation frequency according to crop growth and nutrient demand. Rawat *et al.* (2023) [22] reported that stage-wise fertigation based on crop nutrient demand improved tomato productivity under naturally ventilated polyhouse conditions. Application of 100% RDF (300:150:150 kg N: P₂O₅:K₂O

ha⁻¹) with nutrient application synchronised to different growth stages produced the highest fruit yield of 180.4 t ha⁻¹, compared with 145.2 t ha⁻¹ under farmers' practice, representing a 24.3% increase in yield. The study indicated that synchronising NPK application with crop growth stages improves nutrient-use efficiency, water-use efficiency and economic returns. Tumbare *et al.* (2002) [23] found that weekly fertigation through 14 equal splits benefited tomato. Frequent applications can help maintain nutrient availability without exposing a large quantity of soluble fertilizer to leaching at one time.

10. Nutrient distribution in the root zone

The spatial distribution of nutrients depends on the interaction between fertilizer movement and the irrigation wetting pattern. Conventional soil application followed by surface irrigation can produce uneven nutrient movement, whereas drip irrigation concentrates water near the root zone. Drip fertigation adds dissolved nutrients directly to this wetted region and therefore offers greater control over placement and timing. (Thomas *et al.*, 2024) [24]. Soil fertiliser application with traditional irrigation water: nutrient distribution is influenced by runoff, infiltration, deep percolation and soil heterogeneity. Soil fertilizer application with drip irrigation: water placement is precise, but nutrient movement still depends on soil redistribution and fertilizer dissolution. Drip fertigation: water and soluble nutrients are delivered together, allowing frequent and localised nutrient supply. Drip fertigation is the most efficient approach for precision farming and resource conservation

In sandy or coarse-textured soils, nutrient movement can be rapid because of high infiltration and relatively low nutrient retention capacity. Frequent small fertigation doses can therefore reduce the amount of soluble nutrient exposed to downward movement at any single time, provided irrigation is not excessive.

11. Boosting crop growth through drip fertigation

Fertigation has developed as an effective nutrition management approach that enhances plant growth and development by precisely and timely applying water-soluble nutrients through irrigation water. Fertigation improves nutrient availability and uptake by allowing for real-time adjustment of nutrient concentrations and ratios based on crop growth stages and environmental conditions, thereby improving key growth attributes such as plant height, root development, shoot elongation, leaf area, branching, and overall plant vigour.

Several studies have reported improved growth of vegetable crops under fertigation. Nikzad *et al.* (2020) [25] observed maximum plant height and plant spread with 100% RDF applied in 12 equal splits at 5-day intervals in cabbage with fertigation compared with conventional fertilization. In chilli, fertigation with 180:120:180 kg N: P₂O₅:K₂O ha⁻¹ using water-soluble fertilizers resulted in higher plant height (104.27 cm), number of branches plant⁻¹ (16.71) and leaf area plant⁻¹ (89.44 dm²) than conventional fertilizer application (Reddy, 2017) [26]. In tomato, fertigation with 75% K and 100% N and P produced the highest plant height (77.6 cm), root length (17.2 cm) and plant dry weight (107.2 g) among the treatments studied (Reddy *et al.*, 2022) [27]. Similarly, Savitha *et al.* (2010) [28] reported that applying 75% RDF through fertigation resulted in greater plant height, number of leaves plant⁻¹ and root length in both big onion and aggregate onion compared with soil application. Gupta *et al.* (2010) [29] found that fertigation with 60% of the recommended NPK dose produced the highest plant height (132.4 cm), primary branches plant⁻¹ (8.20) and number of nodes on the main stem (29.2) in tomato compared with higher fertigation levels and soil-applied fertiliser. In broccoli, application of the recommended fertilizer dose (120:60:60 kg N: P₂O₅:K₂O ha⁻¹) through fertigation significantly improved plant height and number of leaves plant⁻¹ under Tarai conditions of Uttarakhand (Debbarma *et al.*, 2021) [30]. Overall, these findings indicate that drip fertigation can enhance vegetative growth by improving the timing, availability and uptake of nutrients, with the magnitude of response depending on crop, nutrient dose and fertigation schedule.

12. Fertigation for higher crop productivity

Drip fertigation improves yield attributes by maintaining favourable soil moisture and nutrient availability within the active root zone, thereby supporting efficient nutrient uptake and assimilate partitioning towards reproductive organs. Several studies have reported significant improvements in yield attributes of different crops under drip fertigation. Rajalingam *et al.* (2022) [31] reported that fertigation with 150:100:150 kg N: P₂O₅:K₂O ha⁻¹ produced the highest fruit yield of 5.53 kg plant⁻¹ and 37.11 t ha⁻¹ compared with conventional fertilizer application. In chilli, fertigation increased dry chilli yield by 27.87–52.40% over furrow irrigation combined with conventional fertilizer application (Reddy *et al.*, 2016). Similarly, application of 125:100:125 kg N: P₂O₅:K₂O ha⁻¹ through fertigation increased chilli yield by 14.84–61.55% compared with the control treatments (Nair *et al.*, 2023) [32]. Patil *et al.* (2015) [33] recorded the highest capsicum fruit yield under drip irrigation at 100% evaporative replenishment combined with 75% of the recommended nitrogen dose. In chilli, fertigation with 263:60:345 kg N: P₂O₅:K₂O ha⁻¹ resulted in the highest fruit weight compared with the conventional fertilizer recommendation of 75:40:25 kg N: P₂O₅:K₂O ha⁻¹ (Das *et al.*, 2026) [34]. Anjum *et al.* (2022) [35] also reported the maximum cucumber yield of 66.71 t ha⁻¹ with fertigation at 80% of the recommended fertilizer dose. These findings indicate that appropriate fertigation levels can improve yield attributes such as fruit weight, fruit yield per plant and total yield, although the optimum nutrient dose varies with crop, growing conditions and fertigation schedule. Basavaraju *et al.* (2014) evaluated fertigation levels in coconut over several seasons. The pooled nut yield increased from 68.31 nuts palm⁻¹ in the unfertilized control to 95.26 nuts palm⁻¹ under 100% NPK through drip fertigation. The 75% treatment produced 87.41 nuts palm⁻¹, while 100% NPK through soil application produced 87.57 nuts palm⁻¹.

13. Effect of fertigation on nutrient use efficiency

Nutrient-use efficiency (NUE) describes how effectively absorbed or applied nutrients are converted into biomass or economic yield. Fertigation can improve NUE by increasing the temporal and spatial coincidence between nutrient availability and plant demand. Nutrient-use efficiency (NUE) reflects the effectiveness with which applied nutrients are utilized by crops. Drip fertigation can improve NUE by supplying nutrients in small, frequent and localized applications, thereby maintaining nutrient availability in the active root zone and reducing losses. Gupta *et al.* (2015) [36] reported that drip irrigation at 80% ET combined with 60% RDF through fertigation recorded fertilizer-use efficiencies of 10.9, 18.3 and 27.4 q kg⁻¹ N, P and K, respectively. In chilli, Singh *et al.* (2017) [37] found that the highest nutrient-use efficiency was obtained with 50% RDF through fertigation combined with two foliar sprays of 1% urea phosphate, indicating that efficient nutrient application can improve fertilizer utilization even at a reduced fertilizer dose. Similarly, Sandal *et al.* (2015) [6] evaluated 50, 100, 150 and 200% RDF through fertigation in broccoli and reported that the 50% RDF fertigation treatment recorded high nutrient-use efficiency, with savings of 50% fertilizer and 20–60% water compared with conventional fertilization while maintaining comparable yield levels. These findings demonstrate that higher fertilizer application does not necessarily increase nutrient-use efficiency; rather, precise nutrient placement, suitable fertilizer rates and synchronization with crop demand are important for maximizing fertilizer utilization.

14. Enhancing water-use efficiency through drip fertigation

Water-use efficiency (WUE) expresses crop productivity in relation to water use. In fertigation systems, WUE is influenced not only by irrigation quantity but also by the uniformity and timing of water and nutrient delivery. Kumari *et al.* (2014) [38] reported the highest WUE of 5.24 q ha⁻¹ cm⁻¹ with water-soluble fertilizer at 70% RDF under drip irrigation. The study also reported 33.94% water saving with drip fertigation compared with conventional irrigation. In tomato, Sharma

(2017) [39] recorded the highest water-use efficiency of 26.37 kg ha⁻¹ cm with drip irrigation at 50% pan evaporation combined with 75% RDF through fertigation and two foliar sprays of 1% urea phosphate. Dorji *et al.* (2005) [40] compared traditional drip system irrigation to deficit irrigation (DI) for hot pepper. They found that water savings with drip irrigation were about 50 per cent over traditional drip irrigation without affecting marketable yield. Improved fertigation management strategies can reduce water and fertiliser use, minimise nitrate (NO₃⁻) leaching, maintain crop yield, and help to control soil salinity under conditions of limited availability of good-quality irrigation water (Magán *et al.*, 2018) [41].

Environmental significance

The study illustrates how irrigation method changes the fate of applied nitrogen. Fertigation should therefore be evaluated not only by yield response but also by the movement of nutrients below the root zone. The goal is not simply to increase nutrient concentration near the crop, but to maintain sufficient availability while limiting transport to deeper soil layers and groundwater.

15. Fertigation under poly house, hydroponics and soilless system

The results showed that 100% recommended fertilizer through fertigation produced the best performance in cucumber under polyhouse conditions, with productivity reaching up to 720 q ha⁻¹. Protected cultivation provides an environment in which water, nutrients and microclimate can be controlled more closely, making fertigation particularly valuable (Kumar, 2020) [42]. Hydroponics grows plants without soil using mineral nutrient solutions. The nutrient film technique (NFT), deep-water culture, wick systems, ebb-and-flow systems and aeroponics are major hydroponic approaches. (Naresh *et al.*, 2024) [43].

Anusree *et al.* (2025) [44] reported superior tomato growth and yield under an ebb-and-flow system, while Shtaya *et al.* (2022) [45] found NFT to have the highest WUE among the tested lettuce systems. These findings show that fertigation principles extend beyond field drip systems into controlled-environment agriculture. The potential reductions in fertilizer requirement when nutrient-containing reclaimed water is used, but emphasizes the need for adequate treatment. Advanced treatment and disinfection may be required to control contaminants before agricultural use. Wastewater fertigation requires monitoring of nutrient loading, salinity, sodium, pathogens, heavy metals and emerging contaminants. Its sustainability therefore depends on treatment quality, crop selection, application rate and regulatory compliance.

16. Challenges, environmental risks and future research

16.1 Emitter clogging

Clogging can be physical, chemical or biological. Suspended particles may cause physical blockage, precipitation of dissolved minerals may produce chemical deposits, and microbial growth can produce biological blockage. It was reported to be around 37% biological clogging, whereas physical clogging is 31% and chemical clogging is 22% (Shi *et al.*, 2022) [2].

16.2 Salinity and leaching

Repeated fertilizer application can increase salt concentration in the root zone if irrigation is insufficient to maintain an appropriate salt balance. Conversely, excessive irrigation can move nitrate and other mobile nutrients below the root zone. Effective fertigation therefore requires simultaneous control of fertilizer concentration and irrigation volume.

16.3 Investment and skill requirements

Initial investment in pumps, filters, injectors, valves, automation and drip infrastructure may constrain adoption among smallholders. Maintenance, calibration and water-quality management also require

technical skills.

16.4 Research priorities

- Develop crop and soil-specific fertigation schedules based on real-time crop demand.
- Integrate soil moisture, EC, pH and nutrient sensors with automated fertigation.
- Develop decision-support systems for sandy and other high-leaching soils.
- Improve fertilizer compatibility protocols for locally available irrigation waters.
- Quantify long-term nitrate movement and greenhouse-gas implications.
- Evaluate economic returns for small and marginal farmers.
- Standardize safe protocols for treated wastewater fertigation.

17. Conclusion

Drip fertigation provides an integrated and precise approach to water and nutrient management by delivering soluble fertilizers with irrigation water at controlled rates, frequencies and locations. The reviewed studies demonstrate its potential to improve crop growth, yield, nutrient-use efficiency, water-use efficiency and overall input-use efficiency across different crops and production systems. Its major advantage is the synchronization of nutrient supply with crop demand while maintaining favourable moisture and nutrient conditions in the active root zone. However, fertigation is not automatically efficient and its performance depends on proper irrigation scheduling, fertilizer selection and compatibility, water quality, filtration, injector calibration, pressure control and system maintenance. Emitter clogging, salinity, nitrate leaching, high initial investment and technical requirements remain important limitations. Future development should focus on sensor-based and automated fertigation, crop- and soil-specific nutrient scheduling, real-time monitoring of soil moisture, EC and pH, and site-specific decision-support systems. Thus, when properly designed and managed, drip fertigation can serve as a key technology for precision agriculture, resource conservation and sustainable intensification of crop production.

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