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REVIEW ARTICLE

Drip fertigation of water-soluble fertilizers: A tool to enhance nutrient and water use efficiency- A comprehensive review

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Abstract

Drip fertigation, which integrates drip irrigation with the application of water-soluble fertilizers, stands out as a highly efficient and sustainable agricultural technique. By delivering precise amounts of water and nutrients directly to the plant root zone, this method optimizes both water and nutrient use, significantly boosting crop yields while minimizing environmental impact. This is especially valuable in arid and semi-arid regions, where water scarcity and soil degradation are major concerns. One of the key benefits of drip fertigation is its ability to drastically reduce water wastage. The targeted delivery system minimizes evaporation, runoff and deep percolation losses, resulting in Water Use Efficiency (WUE) far superior to that of traditional irrigation methods. This is crucial for conserving limited water resources and ensuring the sustainability of agriculture in water-stressed areas. Additionally, the integration of fertilizers into the irrigation system enhances Nutrient Use Efficiency (NUE) by supplying nutrients in amounts closely matched to crop needs. This reduces losses from leaching and runoff, maintains soil fertility and lowers the risk of contaminating nearby water bodies. Drip fertigation also supports better crop growth and yield by providing controlled, stage-specific nutrition, which improves growth parameters such as plant height, leaf area and biomass. This leads to higher yields, improved crop quality and greater economic returns for farmers due to reduced input costs and increased productivity. Overall, drip fertigation not only conserves resources and supports food security but also promotes environmentally responsible and resilient farming practices.

Keywords: crop productivity; drip fertigation; nutrient use efficiency; soil health; sustainable agriculture; water-soluble fertilizers; water use efficiency

Introduction

The intensifying demand for food and agricultural products, driven by population growth and economic development, has placed immense pressure on natural resources, especially water and soil. Sustainable agriculture, which aims to increase productivity while preserving the environment, is crucial to meeting these demands. This approach integrates practices that improve resource use efficiency and minimize environmental impacts, supporting long-term agricultural viability (1). Sustainable agricultural practices are especially significant in regions facing water scarcity, where efficient resource use can substantially improve yields without depleting or damaging the soil (2). Traditional irrigation and fertilization methods present significant challenges to sustainable agriculture. Surface irrigation, the most common irrigation method globally, typically has a field-level efficiency of only 40 %-50 % due to water losses from evaporation, percolation and seepage (3). Additionally, these methods often lead to uneven water distribution, causing both over-irrigation and under-irrigation within a field, which can result in inefficient fertilizer use and increased nutrient runoff. This inefficiency not only leads to waste of resources but also contributes to environmental degradation, such as soil salinization and water pollution (4). Similarly, the use of traditional solid fertilizers in surface irrigation can cause leaching, a process that removes essential nutrients from the soil, reducing their availability to crops and polluting nearby water sources (5).

Drip fertigation, a modern irrigation method, provides a solution to these issues by combining drip irrigation with fertilizer application, allowing for precise delivery of water and nutrients directly to the crop's root zone. This method is particularly advantageous in arid and semi-arid regions where water resources are limited (6). Drip fertigation involves applying water-soluble fertilizers through a drip irrigation system, which reduces nutrient losses and increases nutrient use efficiency by delivering the necessary nutrients in synchronization with the crops' growth stages. By limiting water and nutrient application to the root zone, drip fertigation significantly minimizes leaching and runoff, which contributes to environmental protection and enhanced soil health (7). Compared to surface irrigation, drip fertigation has been shown to improve both water and nutrient use efficiencies dramatically. Studies have reported that drip fertigation can achieve water use efficiencies as high as 90 %, compared to much lower rates in traditional systems (8). This increased efficiency supports sustainable crop production by conserving water resources while enhancing crop yields and reducing fertilizer input. Consequently, drip fertigation stands out as a promising tool for sustainable agriculture, offering a practical solution to some of the challenges associated with conventional irrigation and fertilization methods.

Drip fertigation overview

Drip fertigation is a modern agricultural practice that integrates drip irrigation with fertilizer application, delivering water and nutrients directly to the crop root zone in controlled amounts. This system operates by dissolving water-soluble fertilizers in the irrigation water, which is then distributed to the plants through a network of tubing with small emitters positioned near the plants' roots (9). The main objective of drip fertigation is to deliver exact amounts of water and nutrients to crops, tailored to their specific growth stages and surrounding environmental conditions. Through its controlled application, drip fertigation helps minimize nutrient runoff, reduce water wastage and maximize nutrient absorption by plants, ultimately resulting in higher crop yields and greater efficiency in resource use (10). The process of drip fertigation involves several components that work together to deliver nutrients efficiently. First, water-soluble fertilizers are prepared in a concentrated solution and stored in a tank. This solution is then injected into the main water supply line through a fertigation device, such as a venturi or injector pump, which controls the rate at which the fertilizer solution is added to the water. As water flows through the drip irrigation lines, it carries the dissolved nutrients to the plant's root zone, where they can be easily absorbed by the roots (11). The timing and frequency of fertigation applications are adjusted based on the crop's nutrient requirements at various stages of growth, as well as soil characteristics and environmental factors like temperature and humidity. This adaptability makes drip fertigation a flexible and effective method for nutrient management in agriculture.

When compared with traditional irrigation methods, such as surface and sprinkler irrigation, drip fertigation offers distinct advantages. In traditional surface irrigation, water is applied to the field and distributed by gravity, which often results in uneven water distribution and substantial water losses due to evaporation, percolation and runoff. Studies have shown that traditional irrigation methods typically have a WUE of only 40 %-50 % (12). In contrast, drip fertigation systems can achieve WUE levels as high as 90 %, as water is delivered directly to the roots with minimal losses (13). This improved efficiency is particularly important in water-scarce regions, where conserving water resources is essential to sustainable crop production. Drip fertigation also allows for improved NUE compared to traditional fertilization methods. In conventional fertilization, nutrients are often applied in larger quantities, either as a soil application or as a foliar spray. However, these methods can lead to significant nutrient losses, reducing the availability of nutrients to plants and potentially harming the environment (14). By applying nutrients directly to the root zone in small, regular doses, drip fertigation reduces the risk of nutrient loss and ensures that plants receive a steady supply of essential nutrients. Research indicates that fertigation can increase NUE by up to 60 %, allowing farmers to achieve higher yields with less fertilizer (15). The drip fertigation is one that provides a practical alternative to traditional irrigation and fertilization methods. Its precise delivery of water and nutrients enhances WUE and NUE, contributing to more sustainable agricultural practices. This system is particularly beneficial for high-value crops that require specific nutrient management, as it enables farmers to optimize resources while minimizing environmental impacts.

Fertigation with conventional vs. water-soluble fertilizers

Conventional fertilizers

Conventional fertilizers are typically granular or solid fertilizers that need to be dissolved or mixed with soil for nutrient uptake. When used in drip fertigation, conventional fertilizers present certain challenges due to their limited solubility and potential to clog drip irrigation systems (16). Since these fertilizers often contain insoluble or partially soluble compounds, they may leave residues that obstruct emitters, reducing the efficiency of water delivery and causing uneven distribution (17). Additionally, conventional fertilizers require careful handling and precise preparation to avoid precipitation, which can form insoluble compounds when mixed with water, particularly in hard water (18). In many cases, conventional fertilizers are applied in larger quantities at intervals, leading to nutrient surges that may exceed plant requirements at certain growth stages, while providing insufficient nutrients at other times (19). This uneven nutrient supply can lead to losses through leaching and runoff, especially in soils with low water-holding capacity. Consequently, conventional fertilizers tend to have lower NUE in fertigation systems compared to water-soluble fertilizers (20). Comparison of conventional fertilizers and water-soluble fertilizers in drip fertigation is given in Table 1 (21-24).

Table 1. Comparison of conventional fertilizers and water-soluble fertilizers in drip fertigation

Aspect	Conventional fertilizers	Water-soluble fertilizers	Reference
Solubility	Limited, often requires pre-mixing	Highly soluble, dissolves easily in water	(21)
Risk of clogging	High risk, may require filtration	Low risk, generally does not clog systems	(22)
Nutrient use efficiency	Lower due to uneven application and potential nutrient loss	Higher, provides controlled, steady nutrient delivery	(23)
Environmental impact	Greater risk of leaching and runoff	Reduced risk due to precision in application	(22)
Application flexibility	Limited, generally applied in large intervals	High can be tailored to crop stages	(24)

Water-soluble fertilizers(WSFs)

WSFs dissolve easily in water, making them highly suitable for drip fertigation. Unlike conventional fertilizers, WSFs allow for precise and continuous nutrient delivery, which can be aligned with the crop's specific growth needs. Because of their high solubility, WSFs are less likely to cause clogging in drip systems and they facilitate an even distribution of water and nutrients all over the field (25). This advantage is particularly beneficial in sandy soils or regions prone to nutrient leaching, where WSFs can improve both water and nutrient retention near the root zone. The solubility and formulation of WSFs also enable tailored nutrient mixes that can target specific crop requirements, enhancing NUE and potentially reducing the total amount of fertilizer needed. Studies have demonstrated that drip fertigation with WSFs can increase NUE by up to 30 % over conventional fertigation practices, leading to improved crop yields and reduced environmental impacts (26). Furthermore, WSFs provide greater flexibility in managing nutrient ratios and application schedules, allowing farmers to adapt fertigation to specific crop stages and environmental conditions, ultimately supporting sustainable agricultural practices. While both conventional and WSFs can be used in fertigation, WSFs offer clear advantages in terms of solubility, nutrient availability and system efficiency. The ability of WSFs to provide precise, regular nutrient applications makes enhanced crop productivity and resource use efficiency (26).

Efficiency and economics of drip fertigation

Drip fertigation has emerged as an effective technique to improve the efficiency of both water and nutrient use in agriculture. The economic advantages of drip fertigation include lower input costs and increased crop yield, making it an attractive option for both large and small-scale farmers.

Increased nutrient and water use efficiency

One of the key benefits of drip fertigation is its ability to significantly improve WUE and NUE. Traditional surface irrigation methods often lose water to evaporation, seepage and runoff, which efficiency levels average between 40 % and 50 % (27). In contrast, drip fertigation can achieve WUE rates of up to 90 %, as water is applied precisely at the root zone, where plants can readily absorb it (28). Similarly by providing nutrients in small and consistent doses, drip fertigation reduces nutrient loss. Studies have shown that NUE can be increased by as much as 30 % with drip fertigation, especially when using WSFs that allow for more efficient uptake by crops (29). The pictorial representation of increased NUE and WUE was depicted in Fig. 1.

Cost savings and economic benefits

Drip fertigation offers substantial cost savings by reducing the amount of water and fertilizer required for optimal crop growth. Traditional fertilization methods often involve large, one-time applications of nutrients, which can lead to wastage and inefficient uptake by plants. In comparison, drip fertigation systems allow for precise, ongoing nutrient management, which can reduce overall fertilizer costs by 20 % to 30 % (30). Furthermore, drip fertigation minimizes water usage and farmers can save on water-related expenses, which is particularly beneficial in areas with water scarcity. The efficiency gains of drip fertigation translate into economic benefits by increasing net income and improving the benefit-cost ratio for various crops, such as maize, cotton and vegetables (31). Table 2 shows that drip fertigation outperforms traditional irrigation by boosting water and nutrient efficiency, leading to lower costs, higher yields and reduced environmental impact (32-36). Its resource-saving benefits make it especially suitable for areas with limited water or high input costs, supporting more sustainable agriculture.

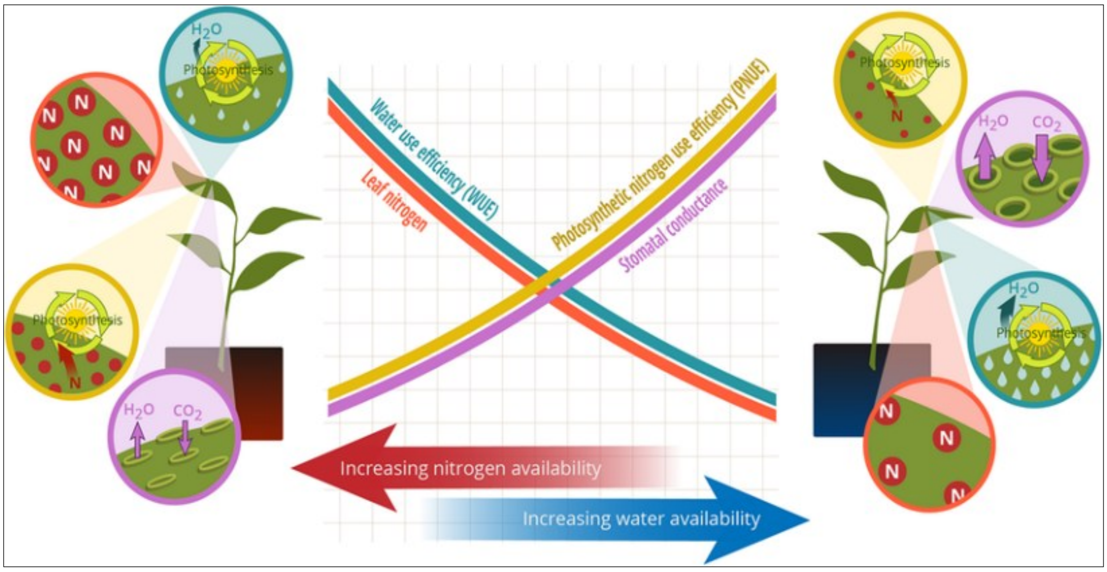

Fig. 1. Process of increased NUE and WUE by using WSFs.

Table 2. Efficiency and economic benefits of drip fertigation vs. traditional methods

Parameter	Drip fertigation	Traditional irrigation	Reference
Water use efficiency (WUE)	Up to 90 %	40-50 %	(32)
Nutrient use efficiency (NUE)	20-30 % higher than conventional	Lower due to leaching and runoff	(33)
Fertilizer cost savings	Up to 30 %	Minimal	(34)
Crop yield increase	20-30 % for crops like tomatoes, maize	Lower yield compared to fertigation	(35)
Benefit-cost ratio	Higher Benefit cost ratio observed in studies	Lower economic returns	(36)

Case studies on crop yield improvements

Drip fertigation has demonstrated its capacity to enhance crop yields across a variety of agricultural settings. In a study on tomatoes, drip fertigation improved fruit yield by 22 % compared to traditional furrow irrigation, primarily due to the increased availability of nutrients and water at the root zone (37). For crops like maize, drip fertigation increased grain yield by nearly 30 % while using less water, which demonstrates the technique's potential to support sustainable, high-yield agriculture (38). Additionally, in arid regions where water is a limiting factor, drip fertigation in watermelon cultivation has led to improved yield and quality by ensuring adequate water and nutrient supply throughout the growing season (39).

WUE

Conservation of water resources

The conservation of water resources is a significant benefit of adopting drip fertigation technology. Traditional irrigation methods such as surface and furrow irrigation are often inefficient, leading to substantial water losses due to factors like evaporation, seepage and runoff. Studies indicate that these systems can lose between 40 % and 60 % of water applied, which is especially concerning in regions where water scarcity is a growing issue (40). Drip fertigation, by contrast, delivers water directly to the root zone of crops, which can achieve water use efficiencies as high as 90 % (41). This efficiency not only conserves water but also enables sustainable farming practices in areas where water availability is limited. The water-saving benefits of drip fertigation make it especially valuable in arid and semi-arid regions where water resources are scarce. For example, implementing drip systems in these regions can extend the agricultural use of water resources and help stabilize food production despite seasonal or climatic variations. Additionally, drip fertigation applies water uniformly and with precise timing, supporting the natural water needs of crops, reducing stress and improving overall plant health (42).

Impact on crop yield and water productivity

Enhanced WUE through drip fertigation positively impacts both crop yield and water productivity. Water productivity refers to the yield output per unit of water used, a crucial measure in regions facing water scarcity. Studies have demonstrated that crops under drip fertigation often yield significantly more per litre of water compared to those irrigated using traditional methods (43). For instance, drip fertigation has been shown to increase crop yield by 20 % to 30 % in various crops, including tomatoes, maize and cotton, compared to conventional irrigation methods. The ability to regulate water supply with drip fertigation allows farmers to optimize water application to match critical crop growth stages, which maximizes productivity. Drip fertigation's precise water delivery also reduces water stress on crops, resulting in more consistent yields and higher-quality produce (44). Consequently, the impact of drip fertigation on crop productivity makes it a valuable technology in sustainable agriculture, where increased yield per unit of water is essential.

Comparative data on WUE with various crops

Drip fertigation's effect on WUE has been well-documented across a range of crops, from high-value vegetables to staple grains. Table 3 provides an overview of WUE for several crops under drip fertigation versus traditional irrigation (45-49). The data shows that WUE can be doubled or even tripled with drip fertigation compared to traditional irrigation, which demonstrates its efficacy in conserving water while achieving higher productivity (50). Results have been observed from other crops, reinforcing drip fertigation's role in water conservation and yield enhancement (Table 3).

Nutrient distribution and uptake

Enhanced nutrient uptake with water-soluble fertilizers

Using water-soluble fertilizers in drip fertigation enhances nutrient uptake efficiency, as these fertilizers dissolve easily in water, making essential nutrients readily available to plants. Unlike conventional fertilizers, which must undergo dissolution and absorption processes in the soil. WSFs provide immediate access to nutrients, aligning with the plant's growth stages and reducing nutrient stress (51). This immediate availability increases the efficiency of nutrient uptake, leading to improved crop growth and higher yields. Studies have shown that WSFs can increase nutrient uptake efficiency by up to 25 % compared to traditional fertilization methods (52). In addition, WSFs allow for more controlled nutrient delivery, ensuring that plants receive nutrients at optimal levels and times. This is particularly valuable for crops with high nutrient demands or sensitive growth stages, as the precise nutrient application minimizes the risk of nutrient imbalances, which can impair growth and reduce yield (53).

Distribution patterns in soil profiles

Drip fertigation provides a controlled and uniform distribution of nutrients within the soil profile, concentrating nutrients in the root zone and minimizing uneven distribution. In traditional irrigation methods, nutrient distribution can be highly variable, leading to areas of nutrient deficiency or excess. Drip fertigation, however, creates a concentrated nutrient zone directly around the root system, optimizing nutrient availability and encouraging deeper root growth (54). This spatial control of nutrient distribution helps maintain a consistent nutrient supply, especially in soils with varying textures and compositions, where uneven nutrient spread can hinder plant growth. Table 4 demonstrates typical nutrient distribution patterns for different irrigation methods. Compared to conventional methods, drip fertigation significantly reduces nutrient loss and concentrates nutrients where they are most accessible to plant roots (55-56).

Reduction in nutrient leaching and environmental impact

One of the most significant environmental benefits of drip fertigation is its reduction in nutrient leaching. In conventional irrigation and fertilization practices, excess nutrients often leach into the subsoil and groundwater, causing pollution and nutrient depletion in the root zone (Fig. 2) (57). Drip fertigation minimizes this risk by delivering nutrients in smaller, more frequent doses, which the plants can readily absorb, reducing the chance of

Table 3. WUE for different crops under drip fertigation vs. traditional irrigation

Crop	Drip fertigation WUE (kg/m^3)	Traditional irrigation WUE (kg/m^3)	Reference
Tomatoes	25.0	12.5	(45)
Maize	2.8	1.5	(46)
Cotton	1.2	0.6	(47)
Watermelon	30.0	15.5	(48)
Onion	12.0	6.8	(49)

Table 4. Comparative nutrient distribution and leaching across irrigation methods

Irrigation method	Nutrient distribution	Leaching potential	Environmental impact	Reference
Surface Irrigation	Uneven nutrient loss in runoff	High	Significant impact due to runoff	(55)
Sprinkler Irrigation	Moderate, some nutrient loss	Moderate	Moderate environmental impact	(55)
Drip Fertigation (WSFs)	Uniform, targeted around roots	Low	Minimal environmental impact	(56)

WSFs - Water-soluble fertilizers

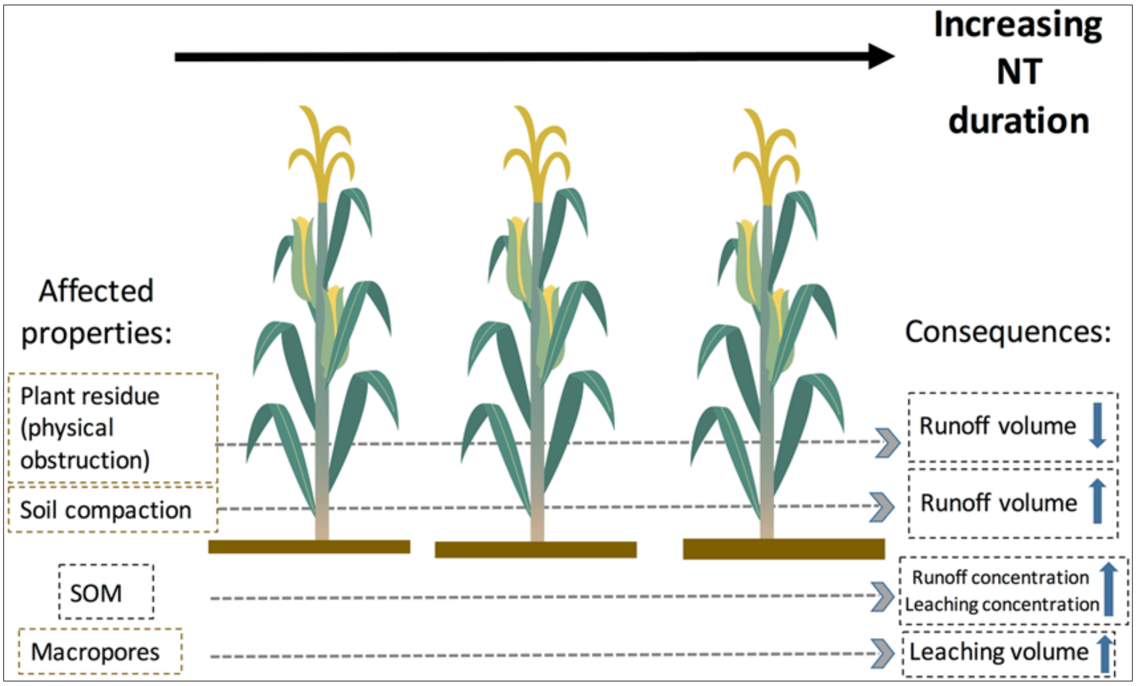

Fig. 2. Diagram of nitrogen flow through leaching and runoff.

leaching. This method also minimizes nutrient losses through surface runoff as water is applied directly to the root zone rather than over large soil areas (58). By limiting leaching and runoff, drip fertigation promotes sustainable agricultural practices that protect both soil and water quality.

Impact on crop growth and yield

Effects on growth parameters (e.g. Plant height, Leaf Area Index)

One of the primary benefits of drip fertigation is its positive impact on crop growth parameters, such as plant height and Leaf Area Index (LAI). Research has shown that crops grown under drip fertigation generally achieve greater plant height and LAI compared to those cultivated using traditional irrigation and fertilization methods (59). The precise delivery of nutrients and water to the root zone reduces nutrient stress, promoting uniform growth across the field. For instance, studies on maize and cotton have demonstrated that drip fertigation increases stem height and biomass accumulation, enhancing the plant's ability to photosynthesize efficiently, which ultimately contributes to better crop productivity (59). LAI, an important indicator of crop canopy size and photosynthetic potential, is also positively influenced by drip fertigation. Increased LAI not only improves light interception but also facilitates higher carbon assimilation, which fuels growth and productivity. By delivering nutrients in synchronization with crop growth stages, drip fertigation ensures optimal nutrient availability during critical growth periods, thereby supporting maximum canopy development and increasing overall plant vigour (59).

Yield attributes for different crops (e.g. Cotton, maize and vegetables)

Yield attributes for various crops, including cotton, maize and vegetables are greatly improved with the adoption of drip fertigation. In cotton cultivation, drip fertigation has been shown to enhance boll number and weight, resulting in higher lint yield compared to traditional irrigation methods. A study on cotton under drip fertigation recorded a yield increase of 20 % to 25 %, attributed to the consistent and controlled nutrient application that optimally supports flowering and fruiting stages (60). Similarly, drip fertigation benefits maize by promoting ear length, grain weight and overall kernel number. Research on maize grown under drip fertigation indicated yield increases of 25 % to 30 %, as the uniform nutrient supply reduces competition among plants for resources, thus enhancing yield stability (60). Vegetable crops, such as tomatoes and peppers, also respond positively to drip fertigation, displaying improvements in fruit size, number and quality. The increased fruit yield in vegetable crops is largely due to the precise water and nutrient management, which minimizes physiological stresses that can hinder fruit development and quality (61).

Fertilizer use efficiency in drip fertigation

Fertilizer use efficiency (FUE) is a critical factor in sustainable agriculture and drip fertigation significantly enhances FUE by delivering nutrients directly to the crop's root zone. Unlike traditional methods, where fertilizers are applied in bulk and may be subject to losses, drip fertigation applies nutrients gradually in line with crop demand, minimizing wastage. Studies have shown that drip fertigation can improve FUE by 30 % to 40 %, depending on crop type and soil conditions (62). This higher efficiency not only reduces input costs for farmers but also lessens the environmental impact of fertilizer use, as there is less risk of nutrient loss into surrounding ecosystems. Enhanced FUE in drip fertigation means that crops receive nutrients in a way that maximizes their absorption and utilization. As a result, this method of nutrient delivery not only contributes to increased crop yields but also supports sustainable practices by minimizing nutrient wastage and reducing the likelihood of environmental pollution (63). Drip fertigation with WSFs has a positive impact on both crop growth and yield. By promoting favourable growth parameters, enhancing yield attributes and improving FUE, this method offers an effective approach to achieving higher productivity and sustainability in agriculture.

Environmental and soil health benefits

Drip fertigation provides numerous environmental and soil health benefits by promoting efficient use of water and fertilizers (64). Among the most significant advantages are the reduction in nutrient leaching, prevention of soil degradation and positive impacts on soil microbial activity and structure. These benefits make drip fertigation a sustainable approach for managing resources in agricultural systems, especially in regions with environmental sensitivity and limited water resources (65).

Reduced leaching and soil degradation

Traditional fertilization methods often involve bulk applications of nutrients, which plants cannot immediately absorb. This excess nutrient load often percolates beyond the root zone, entering the groundwater and causing nitrate contamination (66). In contrast, drip fertigation applies nutrients in smaller, consistent doses directly to the root zone, ensuring they are readily accessible to plants and reducing the likelihood of leaching (66). By minimizing leaching, drip fertigation also prevents soil degradation. Excessive leaching of nutrients like nitrogen and phosphorus can lead to nutrient imbalances in the soil, reducing its fertility over time. Moreover, nutrient losses via leaching contribute to environmental issues such as eutrophication, where nutrient-rich runoff stimulates excessive algae growth in water bodies, negatively impacting aquatic ecosystems (67). Drip fertigation's ability to limit nutrient losses thus helps maintain soil fertility and prevents long-term degradation.

Positive impact on soil microbial activity and structure

Soil microbial activity and structure are vital components of soil health, influencing nutrient cycling, organic matter decomposition and soil structure stability. Drip fertigation, by delivering nutrients directly to the plant root zone, fosters a stable nutrient environment that supports beneficial soil microbial communities. Research has shown that the precise, low-volume nutrient application in drip fertigation creates conditions conducive to microbial activity, as it reduces nutrient competition among microorganisms (68).

The improved microbial activity in soils under drip fertigation contributes to the formation of soil aggregates, which are clusters of soil particles that improve soil structure and water infiltration. Enhanced soil aggregation improves root penetration, which in turn supports crop growth. Furthermore, the steady nutrient supply provided by drip fertigation encourages beneficial microorganisms that promote nutrient cycling, such as nitrogen-fixing bacteria and phosphate-solubilizing microbes, resulting in enhanced nutrient availability for crops (69). Table 5 helps to understand soil health indicators between drip fertigation and traditional methods.

The adoption of drip fertigation not only supports beneficial soil microorganisms but also promotes a stable soil environment, allowing for consistent microbial interactions and activity. This contrasts with traditional fertilization, where nutrient levels in the soil can fluctuate significantly due to infrequent, large fertilizer applications. These fluctuations can stress soil microorganisms, potentially disrupting their activity and affecting soil fertility over time (73). The enhanced soil structure and microbial activity fostered by this method further demonstrate its role in maintaining a balanced, resilient ecosystem.

Technological integration with drip fertigation

Drip fertigation has evolved significantly with the integration of modern technologies that improve the efficiency and effectiveness of nutrient and water management in agriculture. Precision agriculture tools such as sensors and automated systems and the concept of climate-smart agriculture, provide farmers with valuable resources to optimize their practices in response to environmental conditions, thereby maximizing productivity and sustainability.

Precision agriculture tools (e.g. sensors, automation)

Precision agriculture is a farming approach that uses advanced technologies to monitor and manage crop needs accurately. When combined with drip fertigation, precision agriculture tools such as soil moisture sensors, nutrient sensors and automation systems help create an efficient system that minimizes water and fertilizer waste. Soil moisture sensors, for instance they detect the exact level of moisture in the soil, enabling the drip fertigation system to apply water only when needed and in precise amounts (74). This precise water management improves WUE, prevents over-irrigation and maintains a consistent soil environment for optimal plant growth. Nutrient sensors play a similar role by measuring nutrient levels in the soil and detecting deficiencies, allowing for the timely application of fertilizers directly to the root zone. These sensors help avoid nutrient imbalances that can stress plants, reduce yield and ensure that plants receive adequate nutrients throughout their growth cycle (75). Automated control systems further enhance precision by adjusting water and nutrient delivery schedules in response to real-time data from these sensors. Automation can include simple

Table 5. Soil health indicators between drip fertigation and traditional methods

Soil health indicator	Drip fertigation	Traditional methods	Reference
Nutrient leaching	Minimal due to targeted application	High, especially with bulk fertilization	(57)
Soil microbial activity	Enhanced, stable nutrient supply	Variable, nutrient fluctuations	(70)
Soil structure and aggregation	Improved aggregation	Less aggregation, more erosion risk	(71)
Soil fertility maintenance	Stable nutrient profile	Risk of nutrient imbalance	(72)
Environmental impact	Reduced pollution and runoff	Higher risk of water pollution	(70)

timers or more sophisticated internet-connected systems that enable remote monitoring and management via smartphones or computer, which makes drip fertigation even more adaptable to changing crop needs and environmental conditions (76). Drones and satellite imagery are also increasingly used in precision agriculture to monitor crop health and detect areas requiring more intensive management. By mapping the field farmers can identify variations in crop health and adjust drip fertigation settings accordingly, targeting specific areas that need additional resources while avoiding over-application elsewhere. This targeted approach leads to better resource allocation, reduced input costs and improved crop productivity.

Potential for climate-smart agriculture

The integration of drip fertigation with climate-smart agriculture practices is essential to addressing the challenges posed by climate change. Climate-smart agriculture aims to enhance agricultural resilience to changing weather patterns while reducing greenhouse gas emissions. Drip fertigation, with its efficient water and nutrient delivery, aligns well with these goals by conserving water, reducing nutrient runoff and minimizing energy consumption associated with water pumping (77). The ability of drip fertigation to adapt to fluctuating weather conditions is crucial in climate-smart agriculture. By using real-time data from weather stations or meteorological sensors, drip fertigation systems can adjust irrigation schedules in response to anticipated rainfall, temperature and humidity changes. This adaptability helps prevent water wastage during rainy periods and ensures adequate irrigation during dry spells, supporting both crop health and resource conservation (78). In regions affected by drought, this precision can significantly improve resilience by maintaining productivity with limited water resources.

Furthermore, the controlled application of fertilizers in drip fertigation reduces greenhouse gas emissions compared to traditional fertilization methods. Conventional practices, which often involve over-application of nitrogen fertilizers which lead to the release of nitrous oxide, a potent greenhouse gas. Drip fertigation's targeted nutrient application limits this risk by providing plants with only the nutrients they need and reducing the potential for emissions related to nutrient runoff and soil nitrogen levels (79). Table 6 provides a comparative overview of drip fertigation and conventional irrigation in terms of key climate-smart indicators, highlighting the advantages of using technology-driven drip systems for sustainable farming (80).

Challenges and Limitations

While drip fertigation offers numerous benefits in terms of water and nutrient efficiency, it also comes with several challenges and limitations. Issues like system clogging, high initial investment and ongoing maintenance requirements can impact the adoption and effectiveness of drip fertigation systems. Understanding these challenges and implementing solutions is essential for maximizing the benefits of this technology.

Issues with system clogging

System clogging is one of the primary challenges associated with drip fertigation, particularly when using water with impurities or fertilizers that leave residues. Clogging can occur due to physical, chemical or biological factors, which obstruct emitters and reduce the efficiency of water and nutrient delivery. Physical clogging is often caused by particulate matter like sand or silt, while chemical clogging may result from mineral deposits such as calcium carbonate, which can precipitate and block emitters (81). Biological clogging is usually caused by algae and microbial growth within the system, especially when organic materials are present in the water source (82). Clogging not only reduces water flow but also results in uneven nutrient distribution, which can lead to variable crop growth and reduced yields. Addressing clogging requires frequent monitoring and cleaning, which can be labour-intensive and costly. Some farmers may avoid drip fertigation altogether because of these maintenance demands, especially in regions with limited access to clean water (83).

Initial investment and maintenance requirements

The initial investment required to establish a drip fertigation system can be high, especially for small-scale farmers. Costs include drip lines, emitters, filters, pumps and fertigation equipment, along with installation expenses. While the long-term benefits of drip fertigation in terms of yield increase and resource efficiency can offset these costs, the upfront financial burden is often a barrier for many farmers (84). Maintenance requirements add further costs over time as systems require regular inspection, cleaning and repairs to ensure optimal performance. Emitters and filters need routine checking and sometimes replacement, especially in systems that are prone to clogging. In addition, the complexity of managing and monitoring these systems may necessitate technical training, which represents an additional investment in terms of time and resources. For small or resource-limited farms, these maintenance demands may outweigh the perceived benefits, deterring farmers from adopting drip fertigation (85)

Solutions to common issues

Several strategies have been developed to address the common issues associated with drip fertigation. To mitigate clogging, using high-quality filtration systems is essential, particularly when the water source contains particulate matter or organic materials. Filters such as sand filters, screen filters or disc filters can effectively remove suspended solids and reduce the risk of clogging (85). Additionally, periodic flushing of the drip lines and cleaning with mild acids or anti-clogging agents can prevent mineral buildup in emitters, thereby prolonging the lifespan of the system. For biological clogging, disinfectants like chlorine or hydrogen peroxide can be used to control microbial growth within the system. Using high-quality WSFs that do not precipitate in water also helps to prevent chemical clogging, ensuring a smooth nutrient flow through the system (86).

Table 6. Comparison of drip fertigation and conventional irrigation for climate-smart agriculture

Aspect	Drip fertigation	Conventional irrigation	References
Water conservation	High, due to precise application	Moderate, with higher losses	(47)
Nutrient efficiency	High, with reduced runoff	Lower, with nutrient leaching	(80)
Energy consumption	Lower with automated systems	Higher with frequent pumping	(44)
Greenhouse gas emissions	Reduced due to controlled fertigation	Higher with bulk fertilization	(47)
Climate resilience	High, with adaptability to weather	Limited, less responsive	(80)

To address the high initial costs and maintenance needs, government programs and subsidies can play a role in promoting drip fertigation by reducing the financial burden on farmers. In regions where these systems are particularly beneficial, financial incentives can encourage adoption, as seen in areas with government-sponsored irrigation schemes (86). Additionally, training programs that provide technical knowledge on system maintenance can empower farmers to manage drip fertigation systems more effectively, reducing the need for costly external support.

Future prospects

The future of drip fertigation lies in the adoption of emerging technologies that enhance precision, efficiency and sustainability in agriculture. Advances in Internet of Things (IoT) devices and artificial intelligence (AI) are shaping the next generation of drip fertigation systems. IoT sensors can collect real-time data on soil moisture, nutrient levels and environmental conditions, which AI algorithms can analyse to optimize fertigation schedules (87). Automated systems powered by machine learning can further refine water and nutrient delivery based on predictive models, adjusting to weather changes and crop needs (88).

Additionally, drone and satellite imaging provide valuable insights for large-scale fertigation, helping identify areas with specific irrigation and nutrient requirements (89). These innovations not only improve resource efficiency but also support climate resilience by allowing farmers to adapt more effectively to changing conditions.

Future research should focus on enhancing sensor accuracy, developing cost-effective AI applications and exploring sustainable materials for drip systems. Such research could make drip fertigation more accessible and affordable, promoting widespread adoption among smallholder farmers (90). Exploring bio-based solutions to reduce clogging issues will also be essential to increase system longevity and efficiency (91).

Conclusion

Drip fertigation with WSFs has proven to be a transformative approach to modern agriculture, particularly in regions where resource conservation and sustainability are paramount. This method integrates the precise application of water and nutrients directly to the plant root zone, maximizing resource efficiency and promoting healthier crop growth. The benefits of drip fertigation with WSFs span across water use efficiency, nutrient utilization, crop yield enhancement and environmental protection, positioning it as a highly effective agricultural practice. One of the primary benefits of drip fertigation lies in its ability to enhance WUE. By delivering water precisely to where it is needed, drip systems minimize wastage through evaporation, runoff and percolation, achieving WUE levels as high as 90 %. This efficiency is particularly valuable in arid and semi-arid regions, where water scarcity is a significant concern. Water conservation through drip fertigation ensures that crops receive an adequate supply of moisture without depleting local water resources, supporting sustainable water management in agriculture. In addition to improving water efficiency, drip fertigation boosts NUE. WSFs, which dissolve easily in water, enable nutrients to reach the root zone directly and in controlled amounts. This controlled application prevents nutrient leaching, reducing environmental contamination and maintaining a balanced nutrient profile in the soil. The precise delivery of nutrients also means that plants receive adequate nourishment throughout their growth stages, resulting in improved crop health and increased yields. Enhanced NUE also translates to cost savings for farmers, as they can achieve better productivity with fewer inputs.

Beyond efficiency in water and nutrient use, drip fertigation significantly impacts crop growth and yield. Growth parameters like plant height, LAI and biomass are positively influenced by the targeted delivery of nutrients and water. This improvement in growth parameters directly correlates with enhanced yield attributes, including fruit size, grain weight and quality of produce across a variety of crops from vegetables to cash crops like cotton. Higher yields achieved through drip fertigation contribute to the economic stability of farms, allowing farmers to maximize their output per unit of land and resources. The importance of drip fertigation with water-soluble fertilizers extends beyond its immediate benefits to farmers; it plays a critical role in the broader goal of sustainable agriculture. As global challenges like water scarcity, climate change and food security become increasingly pressing agricultural practices that conserve resources while ensuring high productivity are essential. Drip fertigation addresses these challenges by fostering efficient use of inputs, enhancing crop resilience and reducing environmental impact. It supports the shift toward climate-smart agriculture by enabling precise resource management that adapts to changing weather patterns and minimizes emissions associated with excessive fertilizer use.

Thus, the drip fertigation with water-soluble fertilizers is a powerful tool for modern agriculture, offering a blend of economic, environmental and productivity advantages. By enhancing resource efficiency, supporting sustainable practices and contributing to food security, drip fertigation stands out as a forward-looking solution that meets the demands of both today and the future. As technology continues to evolve, the integration of drip fertigation with precision agriculture tools and climate-smart practices will further amplify its impact, making it a cornerstone of sustainable agricultural development.

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Authors' contributions

SK conceptualized and designed the review. JP, BA and SR were involved in the collection and organization of literature. ES, RA and BS provided technical inputs and assisted in manuscript drafting. MD contributed to the agronomic perspectives and manuscript refinement. AG supervised the overall preparation and finalized the manuscript. All authors read and approved the final version of the manuscript.

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