Micro-Irrigation and Fertigation for Improving Water Use Efficiency in Fruit Crops — A Review

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Abstract

Micro-irrigation (MI) and fertigation technologies are transformative approaches for efficient water and nutrient management in modern fruit production systems. By delivering water and dissolved nutrients directly to the crop root zone, MI combined with fertigation increases crop water use efficiency (WUE), fertilizer use efficiency (FUE), yield, and fruit quality while reducing environmental losses through runoff, deep percolation and volatilization. This review synthesizes principles, system components, scheduling strategies, fertigation practices, sensor and automation roles, crop-specific findings, environmental and economic benefits, limitations, and future research needs for MI–fertigation in fruit crops.

Keywords: micro-irrigation, fertigation, drip irrigation, water use efficiency, fruit crops, sensors, irrigation scheduling

1. Introduction

Growing scarcity of freshwater resources, increasing urbanization, climate variability, and pressure on existing water supplies have made efficient water and nutrient management vital in horticultural systems. Fruit crops — including perennial trees, vines, and high-value small fruits — are often cultivated under conditions of water stress, especially in arid and semi-arid regions. Water use inefficiency, nutrient leaching, and misuse of fertilizers not only reduce productivity and fruit quality but also pose environmental hazards such as groundwater depletion and soil degradation.

Traditional irrigation methods like flood or basin irrigation result in low water use efficiency (30–40%), whereas micro-irrigation can enhance efficiency up to 80–95%, by supplying water directly to the root zone. Furthermore, fertigation integrates nutrition with irrigation, providing water-soluble fertilizers in frequent and controlled doses. This minimizes nutrient losses through runoff and volatilization, and matches supply with crop demand at different growth stages. Micro-irrigation and fertigation are therefore recognized as key components of precision horticulture and are widely promoted under national missions such as PMKSY (Pradhan Mantri Krishi Sinchayee Yojana) in India.

Recent technological advancements have enabled the use of sensors (soil moisture sensors, tensiometers), automated controllers, remote sensing, and drip scheduling models, allowing farmers to achieve better water use efficiency (WUE) and nutrient use efficiency (NUE). These strategies not only boost yield and fruit quality but also conserve natural resources, aligning with the principles of sustainable and climate-smart horticulture.

2. Principles of Micro-Irrigation and Fertigation

- **Micro-irrigation principle:** supplies small quantities of water at low pressure directly to the root zone through emitters; wetting patterns are localized, minimizing evaporation and runoff. Common MI systems include drip (surface and subsurface) and micro-sprinklers.

- **Fertigation principle:** injects water-soluble fertilizers into the irrigation stream so nutrients are delivered in small, frequent doses during irrigation events. This ensures nutrients are available in the root zone when uptake is highest and reduces losses.

Advantages of integrating MI with fertigation include spatial precision (target root zone), temporal control (aligning nutrient supply with crop demand), lower labour requirements, and potential for automation.

3. System Components and Design Considerations

Key components

- Water source and pump
- Filtration units (sand filters, screen filters) to prevent emitter clogging
- Pressure regulators and flow meters
- Fertilizer injectors (venturi or dosing pumps)
- Lateral lines, emitters (pressure compensating or non-compensating), manifolds
- Valves and automation controllers

Design considerations

- Soil texture and infiltration rate (affect emitter spacing and flow rate)
- Crop root depth and spacing (determine emitter placement)
- Water quality (salinity and suspended solids affect emitter selection and filtration)
- Emitter selection (PC emitters preferred for uniformity)
- Maintenance plans (flushing schedules, filter cleaning)

4. Irrigation Scheduling and Water Use Efficiency (WUE)

Accurate irrigation scheduling is critical to realize the WUE benefits of MI. Common scheduling approaches:

- **Soil moisture-based scheduling:** using tensiometers, capacitance probes or soil moisture sensors to trigger irrigation when soil moisture falls below a crop-specific threshold.

- **Crop evapotranspiration (ETc) based scheduling:** calculating water need from reference evapotranspiration (ETo) and crop coefficient (Kc).

- **Phenology-based scheduling:** aligning irrigation to critical stages (flowering, fruit set, fruit enlargement) and using regulated deficit irrigation (RDI) or partial root-zone drying (PRD) to manipulate yield and quality.

MI systems, when properly sized and scheduled, commonly show large improvements in WUE compared with surface/flood irrigation. Reported system efficiencies for well-managed MI reach values substantially higher than conventional systems.

5. Fertigation Strategies and Nutrient Use Efficiency (NUE)

- **Continuous vs. pulse fertigation:** Continuous low-dose delivery vs. periodic pulses during critical growth stages. Continuous fertigation often improves steady nutrient availability, while pulses may be used for targeted correction.

- **Split nutrient dosing:** dividing seasonal nutrient requirements into multiple fertigation events synchronized with crop demand.

- **Compatibility and solubility:** selection of water-soluble fertilizer formulations (e.g., N as nitrate or ammonium, soluble P and K sources) and ensuring compatibility of mixed solutions.

- **Monitoring EC and pH:** in-line EC/pH sensors help maintain appropriate nutrient concentrations and avoid phytotoxicity or precipitation in lines.

Fertigation increases fertilizer use efficiency by limiting the volume of soil receiving fertilizer, reducing fixation (P) and losses (N leaching), and ensuring nutrient availability during periods of high uptake.

6. Sensors, Automation and Decision Support

Modern MI–fertigation systems adopt sensors and controllers to automate irrigation, measure soil moisture, leaf water potential proxies, sap flow, and microclimatic parameters. Integration with remote telemetry, smartphone apps, and decision support algorithms allows precision scheduling, fertigation titration, and alerts for faults (clogs, leaks). The use of weather stations and ET-based controllers enables dynamic adjustment to environmental variability.

6.1 Role of Automation and Smart Technologies

Modern MI–fertigation systems adopt sensors, controllers, and IoT-based tools to improve decision-making in irrigation and nutrient application. Sensors are used to measure soil moisture, leaf water potential proxies, sap flow, canopy temperature, and microclimatic parameters. These data help determine the exact irrigation requirement and duration, reducing over-irrigation and water wastage.

Integration with remote telemetry, smartphone applications, drones, GIS/GPS tools, and cloud-based decision support systems enables real-time monitoring of orchards. Artificial Intelligence (AI) and Machine Learning (ML) models are increasingly being used for predicting irrigation demand based on crop growth stage, evapotranspiration rate, soil conditions, and weather forecasts.

The use of automated fertigation units helps adjust fertilizer concentration dynamically. ET-based controllers and weather stations assist in irrigation scheduling according to atmospheric demand. These systems can send alerts for faults such as line breaks, clogging, or uneven pressure, ensuring timely maintenance and sustained performance.

6.2 Future Trends in Smart Irrigation

- Use of NDVI sensors and drones for crop health mapping
- Variable Rate Irrigation (VRI) using GPS-based irrigation application
- Integration with satellite remote sensing for evapotranspiration-based scheduling
- Robotic sprayers and autonomous fertigation units
- Solar-powered drip fertigation systems for off-grid areas

7. Crop-specific Findings (selected fruit crops)

7.1 Performance of MI–Fertigation in Major Fruit Crops

- **Citrus (Orange, Lemon, Mandarin):** Drip fertigation improves yield and fruit quality; optimized scheduling reduces alternate bearing and significantly enhances water use efficiency (WUE). Studies have shown up to 35–45% higher yield and 40–50% water savings compared to conventional irrigation.

- **Mango and Guava:** Micro-irrigation with periodic fertigation increases fruit set, enhances fruit size, and advances maturity by 10–15 days in some regions. Controlled irrigation during flowering reduces fruit drop.

- **Grapes:** Regulated Deficit Irrigation (RDI) strategies using drip irrigation improve berry composition, TSS, phenolic content, and wine quality while saving up to 30–40% irrigation water.
- **Banana and Papaya:** Highly responsive crops to fertigation. Multi-split fertigation improves bunch weight, leaf area index (LAI), and nutrient uptake efficiency. Yield increases of 25–35% have been recorded.
- **Strawberry:** Substrate-based drip fertigation in protected cultivation provides fine control over salinity and nutrient levels. EC management leads to improved fruit size, firmness, flavor, and shelf life.

7.2 Comparative Benefits Across Crops

Fruit Crop	Water Saved (%)	Yield Increase (%)	Key Advantages
Citrus	40–50%	35–45%	Less alternate bearing, uniform fruit size
Grapes	30–40%	20–30%	Improved berry composition and wine quality
Mango	25–35%	15–25%	Advanced maturity, better fruit set
Banana	30–45%	25–35%	Higher bunch weight and LAI
Strawberry	40–55%	30–40%	Better shelf life and fruit quality

(These summaries come from multiple field trials, ICAR reports, PFDC research data, and review studies across regions.)

8. Environmental and Economic Benefits

Environmental Benefits

- Reduced water withdrawals and lower groundwater depletion through precise water application.
- Lower nutrient leaching and reduced eutrophication risk in nearby water bodies.
- Reduced soil erosion and salinization risk due to controlled wetting patterns.
- Improved soil health and structure as micro-irrigation avoids waterlogging and maintains ideal soil moisture.
- Better water-use efficiency (40–70% saving) compared to conventional irrigation methods.
- Reduced greenhouse gas emissions due to lesser pumping energy and reduced fertilizer usage.
- Facilitates use of recycled/treated wastewater for irrigation in a safe manner.
- Supports climate-smart agriculture and helps adaptation to drought and erratic rainfall.
- Encourages sustainable land use and conservation of natural water resources.
- Enhanced microclimate around root zone, reducing plant stress and improving physiological activity.

Economic Benefits

- Higher yields and improved fruit quality, leading to premium prices in the market.
- Reduced labor cost due to automation of irrigation and fertigation.
- Lower fertilizer and water input per unit yield, increasing resource-use efficiency.
- Early maturity of fruits, enabling off-season production and better market timing.
- Long-term profitability through reduction in input cost and increase in productivity.

- Better pest and disease management due to reduced humidity on foliage.
- Return on Investment (ROI) depends on crop value, water savings, and system lifespan.
- Possibility of government subsidies under PMKSY, Rashtriya Krishi Vikas Yojana, MIDH, NABARD, etc.
- Increased farm income and employment generation through higher cropping intensity.
- Support for export-oriented fruit crops, improving foreign exchange earnings.
- Helps small and marginal farmers adopt precision farming and become economically stable.

9. Constraints and Challenges

Technical Challenges

- High initial capital investment required for pumps, filters, emitters, controllers, and fertigation units, which may not be affordable to small farmers.
- Emitter clogging due to poor water quality or lack of filtration—necessitating regular flushing and maintenance schedules.
- Need for water-soluble and compatible fertilizers, along with proper knowledge of fertigation chemistry to avoid precipitation and line blockage.
- Uneven wetting patterns in heterogeneous soil types leading to irregular crop growth and non-uniform nutrient uptake.
- Salinity build-up around emitters when saline irrigation water is used, affecting root health and yield in sensitive fruit crops.
- Lack of reliable power supply in rural areas for running pumps, sensors, and automated controllers.
- Limited availability of spare parts and repair services, especially in remote production zones.

Knowledge & Capacity Constraints

- Insufficient farmer awareness and training in system design, scheduling, calibration, and troubleshooting.
- Poor understanding of fertigation scheduling and nutrient formulation, resulting in over/under-application.
- Lack of soil–plant–water monitoring tools for decision-making in smallholder farms.
- Dependence on skilled technicians for system installation and maintenance increases operational costs.

Socio-Economic & Institutional Barriers

- Low adoption among marginal farmers due to limited access to credit and subsidies.
- Inadequate extension services and demonstration trials to build confidence in the technology.
- Fragmented land holdings make system layout difficult and may reduce its economic viability.
- Lack of standardized fertigation protocols for different agro-climatic zones and fruit crop types.

10. Best Management Practices (BMPs)

- Proper system design as per soil type, crop, water quality and ET rate.
- Use of efficient filtration system – sand filter, screen filter, hydro-cyclone.
- Pressure-compensating emitters for uniform distribution.
- Sensor-based scheduling – moisture sensors, tensiometers, IoT devices.
- Monitoring EC and pH during fertigation to avoid precipitation.
- Use of water-soluble fertilizers only.
- Periodic soil and leaf testing for nutrient adjustment.
- Regular maintenance & flushing of emitters and pipes.

- Training for farm staff on fertigation chemistry and troubleshooting.
- Record keeping of water use, fertilizer dose, and plant response.

11. Conclusions

Micro-irrigation and fertigation represent a modern, resource-efficient, and sustainable approach for fruit crop production, especially in water-scarce and climate-vulnerable regions. By delivering precise amounts of water and nutrients directly to the active root zone, these technologies significantly enhance Water Use Efficiency (WUE), Nutrient Use Efficiency (NUE), yield, and fruit quality while reducing environmental losses such as runoff, leaching, and evaporation. Integration of advanced tools such as soil moisture sensors, ET-based scheduling systems, automation, AI–ML-based decision support tools, and smart fertigation controllers has further strengthened the role of MI–fertigation in precision horticulture. The adoption of these techniques has shown remarkable improvements across various fruit crops such as citrus, grapes, mango, banana, guava, and strawberry, leading to 30–50% water saving and 20–40% yield enhancement in many studies. However, challenges such as high initial investment, lack of technical knowledge, emitter clogging, fertigation compatibility issues, and uneven adoption among small farmers remain limitations. Therefore, capacity building, government support, subsidies, training, crop-specific models, and long-term field research are essential to promote large-scale adoption.

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