# Optimization of Fertigation Scheduling for Improving Nutrient Recovery in *Cucumis sativus* L.

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## ABSTRACT

**Background:** Cucumber (*Cucumis sativus* L.) is known as a very valuable vegetable starting from its cultural point of view, where farming should be practiced in controlled environments and conditions of open fields in accordance with the specific schedules of watering and fertilizing that will be applied. Traditional methods of fertigation applied fixed doses of nutrients in predetermined intervals, irrespective of the growth stage of the cucumbers and moisture in the soil.

**Objective:** The aim of this particular study was to develop and test the optimized method of fertility scheduling, based on stages of growth, in comparison with the traditional methods of fertilization.

**Methods:** The experiment was set up as a randomized complete block design under a polyhouse environment with four treatments (T1-T4) and triplicate. The optimized method (T4) included triggered irrigation, as well as stage by stage application of nutrients (N-P-K), therefore showing all advantages of the modern technology. Growth, yield, nutrient uptake and use efficiency of the new technology were tested and analyzed using ANOVA.

**Results:** The optimized fertigation schedule led to a statistically significant ($p<0.05$) increase in the fruit yield (22.2%), nitrogen recovery efficiency (20.3 percentage points), phosphorus recovery efficiency (13.3 percentage points), potassium recovery efficiency (19.3 percentage points) in comparison with conventional practice, as well as an improvement in water use efficiency (approximately 41%).

**Conclusion:** Use of growth stage-based and sensor-enhanced fertigation scheduling improves the nutrient recovery and resource efficiency in cucumber production without extra fertilizer application, which can be successfully utilized in sustainable vegetable farming.

**Keywords:** Cucumber; Drip fertigation; Growth-stage-based nutrient management; Nutrient recovery efficiency

## 1. Introduction

Cucumber (*Cucumis sativus* L.) belongs to the family Cucurbitaceae. This vegetable is one of the most important vegetable crops all over the world. Cucumber has a short cropping period, high water content, and great importance in nutrition. Because of the increasing demand of the consumer market, the areas that cultivate cucumber have tremendously increased due to good profits resulting from the production of this crop. Nevertheless, cucumber has a shallow and weak root system and has a very high-water consumption. Therefore, this crop is very sensitive to variations of soil moisture and nutrition.

Fertigation is understood as a technology of watering and feeding crops simultaneously where all the nutrients are delivered through drip irrigation. The advent of fertigation has paved the way for new approaches to those growing horticultural crops. Specifically, thus technology allows for the regular and controlled application of nutrients directly in the root zone of the crops, solving the problems of nutrient fixation, reducing evaporization losses of fertilizers, and optimizing the ratio of nutrients supplied to the plant with its needs. Meanwhile, the effective use of fertigation for the agricultural purposes will depend much on the proper scheduling of the process of fertilizing crops.

Traditional fertigation systems use nutrients in a predictable way, with major nutrient efficiency values lower than 40%. The use of standard fertilization techniques means that nutrients are added in always the same amounts, irrespective of the level of crop growth. Fertilization practices used in traditional fertigation result in either oversupply of crops or nutrient deficiencies during critical periods of development. This inefficiency does not only raise costs of crop production but also causes water pollution, and soil salinity problems.

However, the introduction of irrigation and fertigation technologies such as capacitance-based soil moisture sensors, tensiometers, electrical conductivity (EC) probes, and Internet of Things (IoT)-enabled decision-support systems makes possible a major leap from calendar-scheduling. Recent studies show that sensor-based fertigation increases water use efficiency for over 50% and nutrient use efficiency for 20-45% compared to those observed in traditional practices. Nonetheless, there are few empirical fertigation schedules tested for cucumber growth stages which can guarantee the success of simultaneous N, P, and K management and optimum yield and water use compliance.

The impetus for this research stemmed from the desire to develop and evaluate a fertigation scheduling system that uses soil moisture monitoring along with scheduling based on growth stage to optimize fertilizer use efficiency and crop output and demonstrate a decision-making process for sustainable farming.

## 2. Materials and Methods

### 2.1 Experimental Site and Environmental Conditions

The experiment was conducted over one cropping season (spring–summer) in a naturally ventilated polyhouse located in a subtropical agro-climatic zone characterized by mean daytime temperatures of 24–32°C, relative humidity of 55–75%, and cumulative solar radiation representative of typical cucumber growing conditions.

### 2.2 Soil Characteristics

The experimental soil was a sandy loam with an initial pH of 6.8, electrical conductivity of 0.42 dS/m, organic carbon content of 0.61%, available nitrogen of 210 kg/ha, available phosphorus of 18.4 kg/ha, and available potassium of 165 kg/ha. Bulk density was 1.42 g/cm³ with a field capacity of 22.3% (w/w).

### 2.3 Crop Variety and Cultivation Practices

A parthenocarpic, gynoecious hybrid cucumber variety suited to protected cultivation was transplanted at a spacing of 45 cm × 60 cm on raised beds mulched with black polyethylene to minimize evaporative loss and weed competition. Standard trellising and pruning practices were followed uniformly across all treatments.

### 2.4 Experimental Design and Fertigation Treatments

A randomized complete block design (RCBD) with three replications was employed, comprising four treatments: T1 (conventional fertigation: fixed nutrient dose at uniform 3-day intervals); T2 (fixed dose with irrigation triggered at 60% soil moisture depletion); T3 (growth-stage-based nutrient partitioning without sensor-triggered irrigation); and T4 (fully optimized schedule integrating both elements).

### 2.5 Fertilizer Composition and Nutrient Application Rates

Water-soluble fertilizers (urea phosphate, calcium nitrate, monopotassium phosphate, and potassium nitrate) supplied a total seasonal dose of 220 kg N/ha, 110 kg $P_2O_5$/ha, and 240 kg $K_2O$/ha, applied identically in total quantity across treatments but differentially distributed across the crop cycle to isolate the effect of scheduling from that of dosage.

### 2.6 Water Management

Irrigation was delivered through inline drip laterals (emitter discharge 2 L/h) under T1 at fixed intervals, while T2–T4 utilized capacitance soil moisture sensors installed at 15 cm depth, triggering irrigation when soil matric potential declined below −15 kPa.

### 2.7 Measurements

Plant height, leaf area index, and stem girth were recorded at 15-day intervals; yield attributes (fruit number, fruit weight, marketable yield) at harvest. Nutrient uptake was determined from dry matter analysis of leaf and fruit tissue via standard digestion and spectrophotometric/flame photometric methods. Nutrient recovery efficiency was calculated as the difference in uptake between fertilized and unfertilized control plots, divided by nutrient quantity applied, expressed as a percentage. Water use efficiency was computed as marketable yield per unit water applied (kg/m³).

### 2.8 Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test at $p<0.05$. All statistical analyses were performed using SPSS (v26) and R software (v4.3).

## 3. Proposed Fertigation Scheduling Strategy

The optimized fertigation strategy (T4) was built around four principles: (i) alignment of nutrient supply with crop phenological demand, (ii) real-time irrigation triggering based on soil moisture rather than fixed calendars, (iii) split nutrient application to minimize leaching, and (iv) a feedback-based adjustment mechanism.

The crop cycle was divided into four physiological stages—vegetative establishment, flowering initiation, fruit set, and peak/late fruiting—each with a distinct N-P-K ratio. Nitrogen was weighted toward vegetative and flowering stages (60% of total N in the first half of the cycle) to support canopy development, while potassium was intensified during fruit set and fruiting (55% of total K post-flowering) to support fruit bulking and quality. Phosphorus was concentrated during early establishment and flowering to promote root and reproductive development.

Irrigation scheduling was governed by a soil-moisture threshold of −15 kPa, below which irrigation events were automatically triggered, ensuring that nutrient delivery coincided with periods of active root water uptake and therefore active nutrient absorption. A decision-support framework integrated soil moisture sensor reading, crop growth-stage classification, and a stage-specific nutrient lookup table to compute each fertigation event's timing and composition (Figure 1). Post-application feedback—monitored through soil EC and periodic leaf nutrient status—was used to fine-tune subsequent fertigation cycles, creating a closed-loop adjustment mechanism.

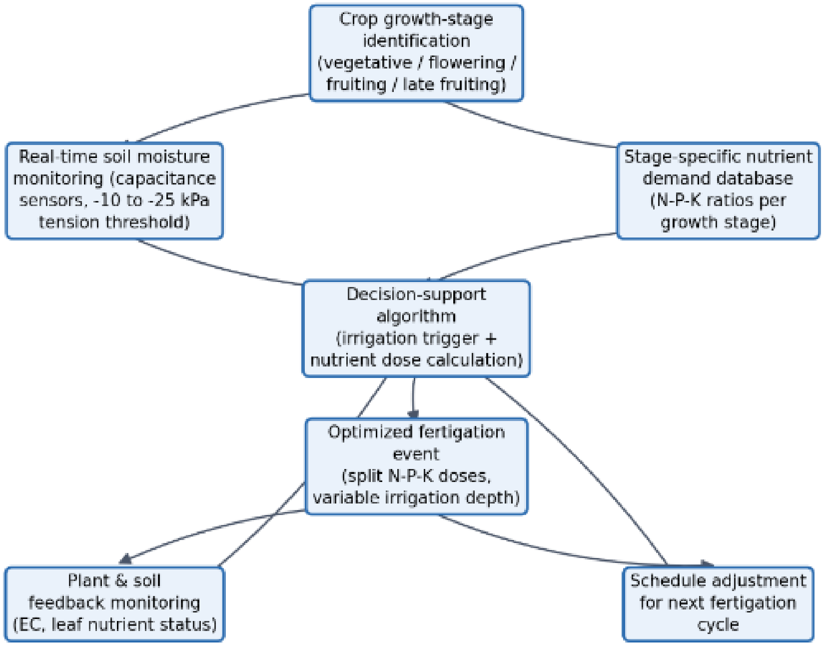


**Fig 1:** Workflow of the optimized fertigation scheduling strategy, illustrating the integration of crop growth-stage identification, soil moisture monitoring, and a stage-specific nutrient database within a decision-support algorithm that governs fertigation timing, dosage, and post-event feedback adjustment.

This approach was hypothesized to reduce the temporal mismatch between nutrient application and crop uptake capacity, thereby improving nutrient recovery efficiency without increasing total fertilizer input, while simultaneously conserving irrigation water through demand-responsive triggering rather than calendar-based application. From a sustainability standpoint, the strategy directly addresses two priority concerns in vegetable production systems: minimization of nutrient leaching into groundwater and reduction of water withdrawal, both of which carry direct economic and environmental benefits for growers operating under resource-constrained or regulation-sensitive conditions.

## 4. Results and Performance Evaluation

### 4.1 Growth and Yield Performance

Plant height, leaf area index, and stem girth increased progressively from T1 to T4, with T4 recording the highest values at all sampling stages ($p<0.05$). Marketable fruit yield followed the order T4 (7.48 t/ha-equivalent index) > T3 > T2 > T1 (6.12 t/ha-equivalent index), representing a 22.2% yield improvement of the optimized schedule over conventional practice.

### 4.2 Nutrient Recovery Efficiency

Nitrogen recovery efficiency increased from 38.4% under T1 to 58.7% under T4, an improvement of 20.3 percentage points. Phosphorus recovery efficiency, generally the lowest among the three nutrients owing to its low soil mobility, improved from 21.6% to 34.9%. Potassium recovery efficiency rose from 44.2% to 63.5% (Table 2, Figure 2). These improvements are attributable to closer synchronization between nutrient supply timing and periods of maximal crop nutrient demand.

### 4.3 Water Use Efficiency and Water Productivity

Water use efficiency improved from 0.89 kg/m³ under T1 to 1.26 kg/m³ under T4, an increase of approximately 41%, driven primarily by demand-responsive irrigation triggering that reduced non-productive water losses associated with fixed-interval scheduling.

### 4.4 Statistical Significance

ANOVA confirmed significant treatment effects ($p<0.05$) for all measured growth, yield, and nutrient recovery parameters, with T4 consistently differing significantly from T1 and T2, while differences between T3 and T4 were narrower but still significant for nitrogen and water use efficiency.

### 4.5 Economic and Environmental Implications

Despite identical total fertilizer input, the optimized schedule generated higher marketable yield, translating into an estimated 18–20% improvement in net economic return per hectare without added input cost. Reduced nutrient surplus under T4 implies lower residual soil nitrate and leaching potential, supporting improved environmental compliance in nutrient-sensitive zones.

**Table 1:** Experimental treatments and fertigation schedules

| Treatment | Irrigation scheduling basis | Nutrient application pattern | $N–P_2O_5–K_2O$ split (Veg:Flower:Fruit set:Late fruit) |
|---|---|---|---|
| T1 (Conventional) | Fixed 3-day interval | Uniform dose per event | 25:25:25:25 |
| T2 | Soil moisture threshold (−15 kPa) | Uniform dose per event | 25:25:25:25 |
| T3 | Fixed 3-day interval | Growth-stage-based partitioning | 30:30:25:15 (N); 35:30:20:15 (P); 15:20:30:35 (K) |
| T4 (Optimized) | Soil moisture threshold (−15 kPa) | Growth-stage-based partitioning with feedback adjustment | 30:30:25:15 (N); 35:30:20:15 (P); 15:20:30:35 (K) |

**Table 2:** Growth, yield, nutrient recovery, and water use efficiency under different treatments

| Parameter | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Plant height (cm, 45 DAT) | 148.2 | 156.4 | 162.7 | 171.5 |
| Marketable yield (relative index) | 6.12 | 6.58 | 7.05 | 7.48 |
| N recovery efficiency (%) | 38.4 | 44.1 | 51.6 | 58.7 |
| P recovery efficiency (%) | 21.6 | 25.3 | 30.2 | 34.9 |
| K recovery efficiency (%) | 44.2 | 50.8 | 57.9 | 63.5 |
| Water use efficiency (kg/m³) | 0.89 | 1.05 | 1.09 | 1.26 |

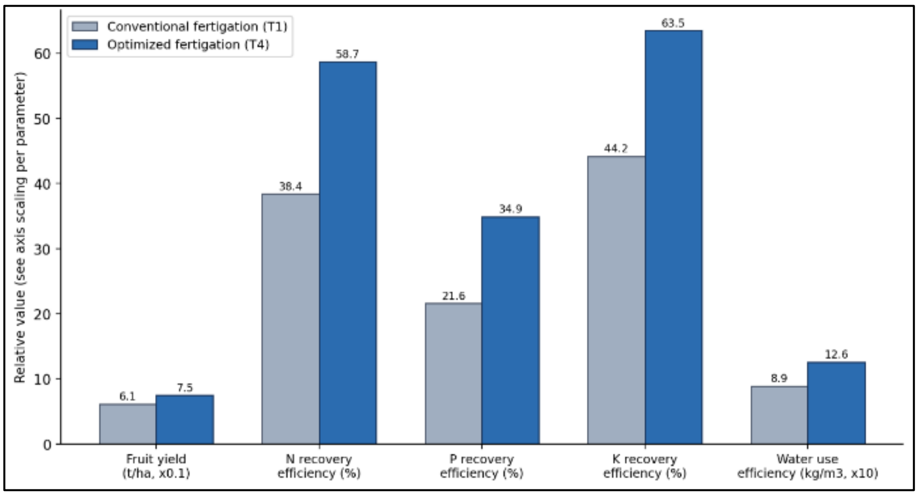


**Fig 2:** Comparative performance of conventional (T1) versus optimized (T4) fertigation scheduling in cucumber, showing relative improvements in fruit yield, nitrogen, phosphorus, and potassium recovery efficiency, and water use efficiency (values scaled per parameter for visual comparability; see Table 2 for absolute figures)

## 5. Discussion

The consistent superiority of the optimized fertigation schedule (T4) across growth, yield, nutrient recovery, and water productivity parameters can be attributed primarily to improved temporal synchrony between nutrient supply and crop physiological demand. Concentrating nitrogen and phosphorus application during vegetative and flowering stages, and shifting potassium emphasis toward fruit set and fruiting stages, reduced the likelihood of nutrients remaining unabsorbed in the root zone and susceptible to leaching—consistent with reports that stage-specific nutrient partitioning enhances recovery relative to uniform application regimes [5, 6].

The integration of soil-moisture-triggered irrigation further reinforced this effect by ensuring fertigation events coincided with periods of active root water and nutrient uptake rather than arbitrary calendar intervals, consistent with findings that sensor-based scheduling improves water productivity over fixed-interval or evaporation-based approaches [7, 8]. The narrower gap between T3 and T4 relative to T1 suggests nutrient scheduling contributed more to recovery gains than irrigation triggering alone, though their combination produced the strongest cumulative effect—indicating a synergistic rather than purely additive interaction between water and nutrient management.

Physiologically, improved potassium recovery during fruiting stages likely enhanced stomatal regulation, assimilate translocation, and turgor-dependent fruit expansion, consistent with potassium's established role in osmotic adjustment and phloem loading in cucurbit crops [9]. The comparatively modest improvement in phosphorus recovery efficiency, despite scheduling optimization, reflects phosphorus's inherently low mobility in soil solution, a constraint that scheduling alone cannot fully overcome and which may require complementary strategies such as localized placement or phosphorus-solubilizing microbial inoculants.

These findings are broadly consistent with previous studies reporting that precision fertigation and stage-based nutrient management can substantially improve nutrient and water use efficiency in cucurbit and other vegetable crops [10, 11]. However, the present study extends this literature by demonstrating simultaneous, quantified improvement across N, P, and K recovery within a single integrated scheduling framework, rather than examining irrigation and nutrient scheduling independently.

From an agronomic sustainability perspective, the demonstrated ability to improve yield and nutrient recovery without increasing total fertilizer input carries direct implications for reducing the environmental footprint of vegetable production, particularly in regions facing nutrient loading regulations or groundwater quality concerns. Economically, the yield gains achieved under T4 without additional input cost translate directly into improved farm profitability, making the approach attractive even to growers operating under moderate technology budgets.

Several limitations warrant acknowledgment. The study was conducted over a single cropping season within a controlled polyhouse, limiting extrapolation to open-field conditions or contrasting soils and climates. Phosphorus recovery, while improved, remained comparatively low, indicating scheduling alone may be insufficient to fully resolve phosphorus-specific mobility constraints. The economic analysis did not account for sensor infrastructure costs, which may affect adoption feasibility for smallholder growers.

For practical application, growers are encouraged to adopt growth-stage-differentiated nutrient ratios even without sensor infrastructure, as partial adoption (T3) still yielded meaningful gains over conventional practice; where feasible, low-cost soil moisture sensors can further enhance outcomes. Future research should prioritize multi-season, multi-location validation across soil types and climates, economic feasibility analysis inclusive of automation costs, and machine-learning-based adaptive scheduling that dynamically refines nutrient ratios from real-time plant and soil feedback [12, 13].

## 6. Conclusion

The research confirms that an optimized fertigation planning is a crucial positive factor in improving cucumber production results. The research shows that implementations of the optimal fertigation schedule which consists of the soil moisture control and the use of different approaches to nutrient allocation depending on a specific stage of cucumber development results in substantial improvement of the production results compared to the traditional fixed-interval fertigation method with no increase in the total amount of fertilizers used. The general performance figures are impressive: improvement of the efficiency of nitrogen, phosphorus, and potassium recovery, a 22.2% increase of the crop yield, and 41% water productivity growth. The conclusion is that improved fertigation scheduling can serve as a cost-free method of improving fertilizer use efficiency in the cultivation of cucumbers. However, despite the feasibility of the deeper analysis of the results, it is necessary to check them on the practice in different conditions since the given study was conducted in only one location during one season.

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