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Adaptive Irrigation Models for Improving Water Use Efficiency in Greenhouse Production

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Abstract. *Greenhouse irrigation management in soilless production systems faces pressure to reduce water and fertilizer consumption while maintaining commercially viable yields. Most documented irrigation approaches rely on one or two measured variables to trigger events, leaving the remaining sensor data unused in the control decision.* ***Purpose.*** *To describe the Smart-Flow Matrix (SFM), an adaptive irrigation management framework that integrates five operational data streams within a unified decision engine, and to present resource-efficiency and yield metrics from its commercial deployment.* ***Method.*** *SFM was deployed in a commercial hydroponic strawberry operation (coconut coir substrate, drip fertigation, greenhouse area up to approximately 10 hectares) in Kyiv Oblast, Ukraine. SFM coordinates volumetric water content, pore-water electrical conductivity, cumulative photosynthetically active radiation, air temperature, and drainage analytics through coordinated threshold logic with seasonal parameter adjustment across three growth stages. Operational records from the SFM period were compared with records from the preceding timer-based management period in the same facility.* ***Results.*** *Water and fertilizer consumption decreased by approximately 45 to 50 percent relative to the timer-based baseline. Yield reached 1.7 to 1.87 kilograms per plant under commercial conditions. Drainage fraction converged to target ranges within three to four irrigation cycles following each parameter adjustment.* ***Conclusion.*** *SFM demonstrates that coordinated multi-parameter irrigation logic with seasonal adaptation can achieve measurable resource savings at commercial greenhouse scale without compromising yield stability.*

Keywords: *adaptive irrigation, water use efficiency, closed-loop control, irrigation optimization, resource efficiency, hydroponic irrigation, greenhouse technology, sustainable agriculture, Smart-Flow Matrix.*

Introduction

Water use efficiency (WUE) in greenhouse crop production has become a central concern for the controlled environment agriculture (CEA) sector. Stanghellini [1] estimates that a well-managed greenhouse in a temperate climate can produce one kilogram of tomato fruit with 15 to 30 liters of water, whereas open-field production of the same crop in a Mediterranean setting requires 60 to 200 liters per kilogram. Soilless cultivation systems amplify this advantage by confining the root zone within a defined substrate volume and delivering water directly to the root surface through drip emitters, reducing evaporative loss and enabling partial or full recirculation of drainage solution [2]. Regulatory pressure on nitrate discharge and rising input costs reinforce the economic case for minimizing water and fertilizer use per unit of marketable yield [4, 9].

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Structural advantages of soilless systems, however, translate into actual resource savings only when the irrigation management logic matches the precision of the delivery infrastructure. Studies on semi-closed tomato production demonstrate that drainage volume and nutrient discharge can be reduced by adjusting fertigation strategy, but the reported magnitude of improvement varies with protocol complexity and the frequency of required recalibration [4, 5]. Putra and Yuliando [3] review soilless WUE literature and conclude that reported efficiency gains range from marginal to substantial depending on the degree to which irrigation timing and volume are synchronized with actual crop demand. Across these studies, the common finding is that hardware configuration alone does not determine WUE; the decision logic governing when, how much, and at what nutrient concentration to irrigate appears to be the principal variable separating high-efficiency operations from those that merely possess the equipment for efficiency.

Process-based adaptive control has been formalized for greenhouse climate management. Körner and Challa [6] develop a humidity control regime that adjusts setpoints according to crop physiological processes and weather forecasts, demonstrating that process-driven logic can outperform static thresholds in energy efficiency. At the irrigation level, Gallardo et al. [7] describe model-assisted scheduling for Mediterranean greenhouses that incorporates crop evapotranspiration estimates, and Incrocci et al. [10] review European greenhouse irrigation practices and identify a gradual shift from calendar-based to sensor-informed management. Seasonal adjustment of irrigation parameters across crop growth stages, however, remains a practice described in grower manuals and commercial platform documentation rather than in peer-reviewed operational studies. No published source presents a complete adaptive irrigation framework that combines multi-stream data integration with explicit seasonal mode switching and documents the resulting resource-efficiency outcomes at commercial production scale.

Purpose of the article. The present article describes the Smart-Flow Matrix (SFM), an adaptive irrigation management framework developed for commercial hydroponic strawberry production, and reports operational metrics from its deployment at greenhouse scale.

Article tasks. (1) describe the SFM system architecture, including its five data streams, conjunctive dual-threshold decision logic, and seasonal mode switching; (2) present water and fertilizer consumption data from the SFM operational period compared with the preceding timer-based baseline in the same facility; (3) report yield performance and drainage-fraction convergence under SFM management; (4) evaluate the resource-efficiency implications of coordinated multi-parameter irrigation at commercial scale.

Literature Review. ***1. Water use efficiency metrics and benchmarks in soilless production.*** Stanghellini [1] argues that the theoretical WUE ceiling for greenhouse crops is determined by the ratio of transpiration to total water input; any water that exits the system as drainage, evaporation from substrate surfaces, or condensation on greenhouse structures represents an efficiency loss. In well-managed closed hydroponic systems, drainage solution is captured and recycled, and substrate surface evaporation is minimized by covering slabs or bags. Under such conditions, Stanghellini [1] reports that WUE can approach 90 percent of the theoretical limit, with drainage fractions below 10 percent. Savvas and Gruda [2] note that most commercial soilless operations, particularly those using open (run-to-waste) configurations, achieve substantially lower WUE because drainage fractions of 30 to 50 percent are maintained deliberately to prevent salt accumulation in the root zone. Converting from open to closed or semi-closed systems reduces water loss but introduces pathogen transmission risk through recirculating solution and requires active management of nutrient imbalance as ions accumulate differentially over successive cycles [2, 5].

Putra and Yuliando [3] compile WUE data across multiple soilless crops and report that substrate-grown vegetables achieve water productivity of 20 to 60 kilograms of fresh product

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per cubic meter of water applied, depending on crop species, system configuration, and management intensity. Strawberry, as a high-value fruit crop with a shallow root zone and relatively low daily water uptake, occupies the upper end of this range when irrigation is well-synchronized with demand [3, 8]. Reported WUE benchmarks, however, rarely specify the irrigation control method used, making it difficult to attribute observed efficiency to hardware (substrate type, emitter spacing) or to management (scheduling logic, threshold selection, seasonal adjustment).

2. Drainage management and nutrient recycling. Massa et al. [4] test three fertigation strategies in semi-closed rockwool tomato production with saline irrigation water (NaCl at 9.5 mol/m^3). Strategy A maintained a conventional open drainage regime. Strategy B incorporated partial recirculation with periodic solution discharge when EC exceeded a predefined ceiling. Strategy C extended recirculation duration by raising the EC discharge threshold. Drainage volume declined progressively from A to C, and nitrate emission in Strategy C fell below the limit imposed by the European Nitrate Directive for surface water discharge. Crop yield did not differ significantly among strategies, indicating that tighter drainage management did not compromise production under the conditions tested [4].

Signore et al. [5] approach nutrient management from the plant-demand side. Using the concept of uptake concentration, the ratio of nutrient mass absorbed to water volume transpired, they formulate a recovery solution that replaces only what the plant has consumed. In a closed NFT cherry tomato system, this approach reduced total solution discharge and maintained EC within a narrower range than a conventional fixed-recipe protocol. The method required frequent analytical measurement of the recirculating solution composition, and the authors note that commercial adoption would depend on the availability of rapid inline nutrient sensors or reliable ion-estimation models [5]. Thompson et al. [9] provide the environmental context for these efforts: in an intensive vegetable production region of southeastern Spain, the authors identify specific irrigation and nitrogen management practices that contribute most to nitrate leaching, and conclude that scheduling precision and drainage fraction control are more effective leaching-reduction tools than blanket reductions in fertilizer application rate.

3. Adaptive and model-based approaches to irrigation scheduling. Körner and Challa [6] identify three physiological processes most sensitive to greenhouse humidity control: calcium transport, powdery mildew development, and vegetative growth rate. Each process requires a distinct relative humidity window operating on a different time scale, and the authors construct a regime that computes a 24-hour setpoint trajectory from weather forecast data while adjusting in real time based on measured conditions. Energy consumption decreased by 19 percent compared with a fixed-setpoint regime. The underlying principle, matching control parameters to specific crop-process requirements with anticipatory-plus-corrective logic, is transferable to irrigation management, where crop water demand similarly varies with physiological stage and environmental conditions [6].

Incrocci et al. [10] review irrigation management practices across European greenhouse vegetable production and identify three levels of scheduling sophistication: calendar-based (fixed timer), sensor-informed (VWC or radiation threshold), and model-assisted (crop evapotranspiration estimate combined with sensor feedback). Adoption rates decline sharply with sophistication level; calendar-based scheduling remains dominant in southern European greenhouse districts despite documented disadvantages. Gallardo et al. [7] report that model-assisted scheduling in Mediterranean greenhouses reduced water application by 15 to 25 percent relative to grower-managed irrigation while maintaining equivalent yield. Silberbush et al. [12] model water and nutrient flow in soilless substrates and demonstrate that plant uptake kinetics vary nonlinearly with solution concentration and root-zone volume, suggesting that static irrigation parameters will systematically misalign with crop demand as root mass and canopy area change across the production cycle.

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4. Strawberry production in soilless substrate systems. Lieten [8] reviews twenty years of strawberry substrate culture in the Netherlands and Belgium, where soilless production expanded from experimental trials in the 1970s to a commercially established system occupying a growing share of protected strawberry area. Typical substrates include peat, coconut coir, and perlite mixes in bag or trough configurations elevated above ground level. Plant densities range from 10 to 12 plants per square meter, and reported yields in well-managed operations reach 5 to 7 kilograms per square meter per production cycle, corresponding approximately to 0.5 to 0.7 kilograms per plant at standard density [8]. Seasonal yield distribution is uneven: a strong early flush followed by a variable mid-season and a declining late-harvest period, with fruit quality and size decreasing as the substrate ages and root-zone conditions become less stable.

Rouphael et al. [11] review the factors that influence vegetable quality in controlled environments and identify root-zone management as a key lever. Substrate moisture fluctuations, EC variability, and temperature stress during critical growth windows each affect fruit dry matter content, sugar-acid ratio, and firmness. For strawberry specifically, excessive irrigation during fruit ripening dilutes soluble solids and accelerates post-harvest softening, while insufficient irrigation during flowering reduces pollination success and fruit set [8, 11]. Irrigation management that adapts to growth stage, maintaining higher VWC during vegetative establishment and controlled mild stress during fruit maturation, has the potential to improve both yield stability and fruit quality, but field validation of these growth-stage-specific irrigation adjustments under measured conditions has not been reported for strawberry cultivated on coconut coir substrate.

Each of the interventions reviewed above, drainage fraction control, nutrient-demand-based solution management, model-assisted scheduling, and growth-stage-specific parameter adjustment, has demonstrated measurable benefits when applied individually or in pairs. What remains undocumented is the cumulative effect of combining these interventions within a single coordinated operational framework. It is unknown whether the resource-efficiency gains from drainage feedback, radiation-responsive scheduling, EC trajectory correction, and seasonal mode switching are additive, partially redundant, or synergistic when applied simultaneously. A system-level evaluation, presenting the combined outcome of all these interventions under commercial conditions, is absent from the reviewed literature.

Materials and Methods. ***1. System architecture.*** Smart-Flow Matrix (SFM) is an adaptive irrigation management framework designed for commercial hydroponic production on inert substrates with drip fertigation. SFM receives five continuous data streams from the greenhouse production environment. At the root-zone level, substrate volumetric water content (VWC) is measured by capacitance sensors embedded in representative cultivation slabs, and pore-water electrical conductivity (EC) is recorded by dielectric sensors adjacent to the VWC probes. Above the canopy, cumulative photosynthetically active radiation (PAR) is integrated from a pyranometer, greenhouse air temperature is recorded by shielded thermocouples at canopy height, and drainage analytics (leachate volume and EC) are measured at collection troughs positioned beneath the cultivation gutters.

Data from all five streams enter a centralized decision engine that operates on two parallel pathways. A feed-forward pathway uses cumulative PAR as an anticipatory input: radiation energy accumulated since the last irrigation event serves as a proxy for transpirational water demand. A feedback pathway continuously monitors VWC, EC, and drainage fraction against target ranges defined for the current growth stage. Irrigation events are authorized only when both pathways converge: the PAR accumulation threshold has been reached AND VWC has depleted below the stage-specific floor. If VWC remains above the floor despite reaching the radiation threshold (indicating low actual water uptake), the event is suppressed and the radiation counter continues to accumulate. Conjunctive dual-threshold logic of this kind

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prevents irrigation on days when accumulated radiation is high but actual plant demand, as reflected in substrate moisture, is low.

2. Coordination rules. **EC trajectory correction.** A three-day rolling average of pore-water EC is computed from the feedback pathway. When the rolling average exceeds the EC ceiling defined for the current growth stage by more than 0.3 dS/m, the VWC floor is lowered by 5 percentage points for subsequent irrigation events, increasing event frequency and drainage volume to flush accumulated salts from the root zone. Once the rolling average returns to within 0.1 dS/m of the ceiling, the VWC floor reverts to its standard value. This rule prevents progressive salt loading over multi-day periods without requiring manual intervention.

Drainage feedback loop. After each irrigation event, measured drainage fraction (leachate volume as a percentage of applied volume) is compared with the stage-specific drainage target. If drainage fraction exceeds the target by more than 5 percentage points for two consecutive events, the irrigation volume per event is reduced by 10 percent. A drainage fraction below the target floor for two consecutive events triggers a 10 percent volume increase. Adjustments are capped at a maximum of two consecutive increases or decreases to prevent overcorrection. This iterative mechanism converges drainage fraction to the target range within three to four adjustment cycles under stable environmental conditions.

3. Seasonal mode switching. SFM operates in three sequential modes corresponding to crop growth stages. In vegetative mode (early growth, root establishment), the radiation sum threshold is set at 150 J/cm^2, VWC target range at 55 to 65 percent, EC ceiling at 1.8 dS/m, and drainage fraction target at 25 to 30 percent. Higher moisture and drainage levels during this phase support rapid root colonization of the substrate and prevent early salt stress. In generative mode (flowering and fruiting), the radiation threshold rises to 200 J/cm^2, VWC range narrows to 45 to 55 percent, EC ceiling increases to 2.2 dS/m, and drainage target decreases to 20 to 25 percent. Narrower VWC range and elevated EC ceiling during this phase are intended to promote fruit quality through moderate controlled stress. In late harvest mode, the radiation threshold rises further to 250 J/cm^2, VWC range drops to 40 to 50 percent, EC ceiling reaches 2.5 dS/m, and drainage target decreases to 15 to 20 percent. Reduced irrigation volume in this phase prioritizes substrate conditioning and minimizes resource input during the period of declining yield.

Mode transitions are initiated manually by the production manager based on visual assessment of crop development stage and are not automated by the system. Once a mode is selected, all four parameter sets (radiation threshold, VWC range, EC ceiling, drainage target) switch simultaneously.

4. Operational context and comparison baseline. SFM was deployed at Berry Commerce, a commercial greenhouse strawberry operation in Vyshniaky, Kyiv Oblast, Ukraine. Production is conducted on coconut coir substrate in elevated gutter systems with drip fertigation. Greenhouse area under SFM management reached approximately 10 hectares. The comparison baseline consists of operational records from the period immediately preceding SFM deployment, during which the same facility operated under conventional timer-based irrigation with fixed intervals and manually adjusted nutrient recipes. Comparison is structured as a before-after analysis within the same facility, not as a concurrent randomized trial. Environmental conditions (greenhouse climate, seasonal radiation patterns, cultivar selection) were comparable between periods but not experimentally controlled.

Results

1. Water and fertilizer consumption.

Comparison of operational records from the timer-based management period with records from the SFM operational period indicates a reduction of approximately 45 to 50 percent in total water applied per crop cycle. With nutrient delivery coupled to irrigation volume in drip fertigation, fertilizer consumption decreased proportionally, and no

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independent fertilizer adjustment was made outside the irrigation schedule. Table 1 summarizes the principal resource parameters.

Table 1. Resource consumption comparison: Smart-Flow Matrix vs. timer-based baseline

Parameter	Timer-based (baseline)	Smart-Flow Matrix	Change
Water consumption (relative)	100%	50–55%	−45–50%
Fertilizer input (relative)	100%	50–55%	−45–50%
Drainage fraction	Uncontrolled (est. 35–45%)	Controlled (20–25%)	Targeted
Irrigation events, sunny day	6–7 (fixed interval)	8–10 (demand-matched)	More frequent, smaller
Irrigation events, cloudy day	6–7 (fixed interval)	3–4 (demand-matched)	Fewer, demand-proportional
Night irrigation events	1–2 (timer continuation)	0 (suppressed by PAR logic)	Eliminated

Source: compiled by the author

Under timer-based management, irrigation events occurred at fixed intervals regardless of weather conditions, and nighttime events continued on the same schedule as daytime ones. SFM eliminated night irrigation entirely: with no PAR accumulation between sunset and sunrise, the radiation threshold was never reached, and the conjunctive logic suppressed all events during dark hours. On sunny days, SFM delivered more frequent but smaller irrigation volumes concentrated during peak-radiation hours, when transpirational demand was highest. On cloudy days, reduced PAR accumulation rate slowed event triggering, and total daily water input dropped to roughly half of the sunny-day volume. Under timer-based management, both sunny and cloudy days received identical water input.

Over the generative period, drainage fraction under SFM converged to the target range (20 to 25 percent) through the iterative volume-adjustment mechanism described in Section 3.2. Under timer-based management, drainage fraction was not measured systematically and is estimated at 35 to 45 percent based on periodic spot checks. Controlled drainage under SFM maintained the fraction within the target range throughout the generative period; substrate replacement was not required between consecutive production cycles in the facility.

2. Yield performance

Table 2 presents yield metrics recorded under SFM management. Yield per plant ranged from 1.7 to 1.87 kilograms across the production cycles observed, with variation observed across cycles that differed in seasonal radiation accumulation and cultivar selection.

Table 2. Yield and production metrics under Smart-Flow Matrix management

Metric	Value	Conditions
Yield per plant	1.7–1.87 kg	Full-season cycle, commercial density
Production scale	≈10 ha	Greenhouse, elevated gutters
Substrate	Coconut coir	Bag configuration, drip fertigation

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Crop	Strawberry (Fragaria × ananassa)	Short-day and day-neutral cultivars
Yield stability across modes	Maintained through seasonal transitions	No decline attributed to mode switching

Source: compiled by the author

Yield per plant was recorded at the end of each production cycle as total marketable fruit weight divided by the number of productive plants. Unmarketable fruit (undersized, deformed, or affected by post-harvest damage) was excluded. Yield stability across seasonal mode transitions was assessed qualitatively by monitoring weekly pick volumes: no abrupt decline in fruit set or average fruit weight coincided with the switch from vegetative to generative mode or from generative to late harvest mode. Fruit quality parameters (soluble solids content, firmness) were not systematically measured during the operational period and are not reported.

3. System behavior across growth stages

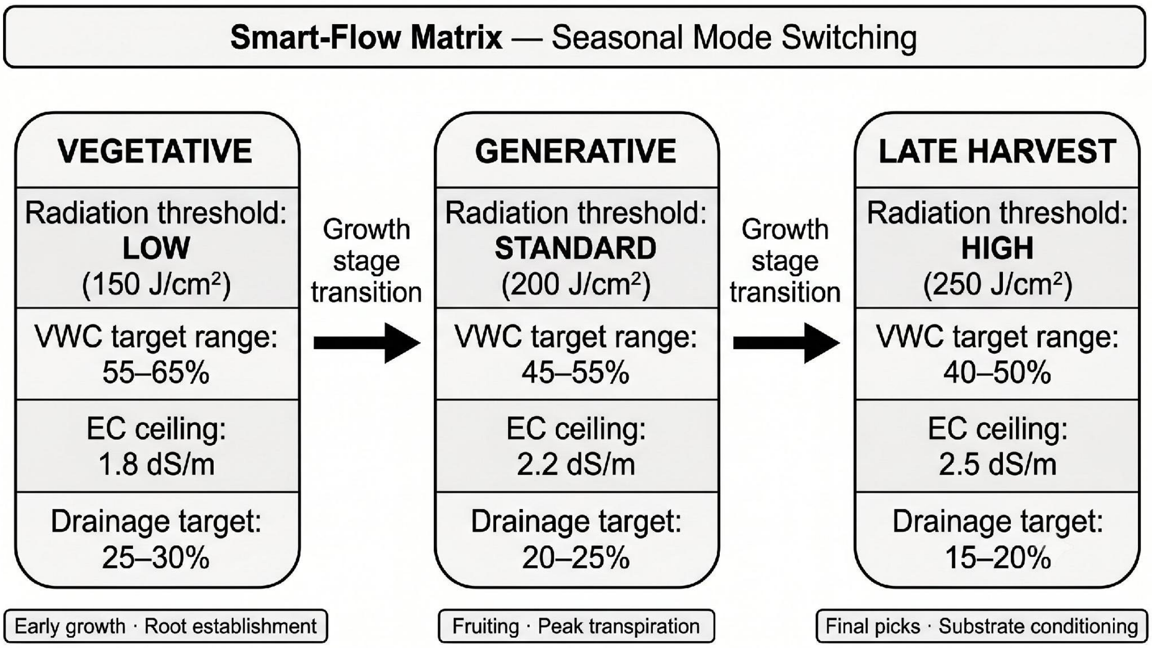

Figure 1. Smart-Flow Matrix seasonal mode switching: parameter sets for vegetative, generative, and late harvest modes

Source: compiled by the author

Figure 1 presents the parameter sets applied in each seasonal mode. Vegetative mode, typically lasting four to six weeks from transplant, maintained higher VWC and drainage fraction to support root colonization of the fresh substrate. Daily irrigation event counts during this phase were lower than in subsequent modes; the low radiation threshold and high VWC floor characteristic of this mode (Figure 1) meant that the conjunctive condition was met less frequently, as the substrate retained sufficient moisture between events. EC remained below the vegetative-mode ceiling throughout this phase without triggering the EC correction rule.

Generative mode, spanning the primary fruiting period of eight to twelve weeks, produced the highest daily event counts. Rising radiation levels in late spring and summer accelerated PAR accumulation, and the generative-mode threshold (Figure 1) generated eight to ten events per sunny day. EC management became active during this phase: on occasions when the three-day rolling average approached the stage-specific EC ceiling, the VWC floor was lowered and

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additional leaching events were triggered automatically. Drainage fraction stabilized near the target range after two to three adjustment cycles at the start of the mode.

Late harvest mode, lasting three to five weeks, was characterized by declining radiation, reduced transpiration, and progressively smaller fruit. Parameter values for this phase (Figure 1) reduced daily event counts and total water input. Lower drainage targets conserved water while allowing moderate salt accumulation as the crop approached the end of its productive cycle. Substrate conditioning during this phase, including periodic high-volume flush events initiated manually, prepared the coir for potential reuse in the subsequent production cycle.

4. Drainage feedback convergence

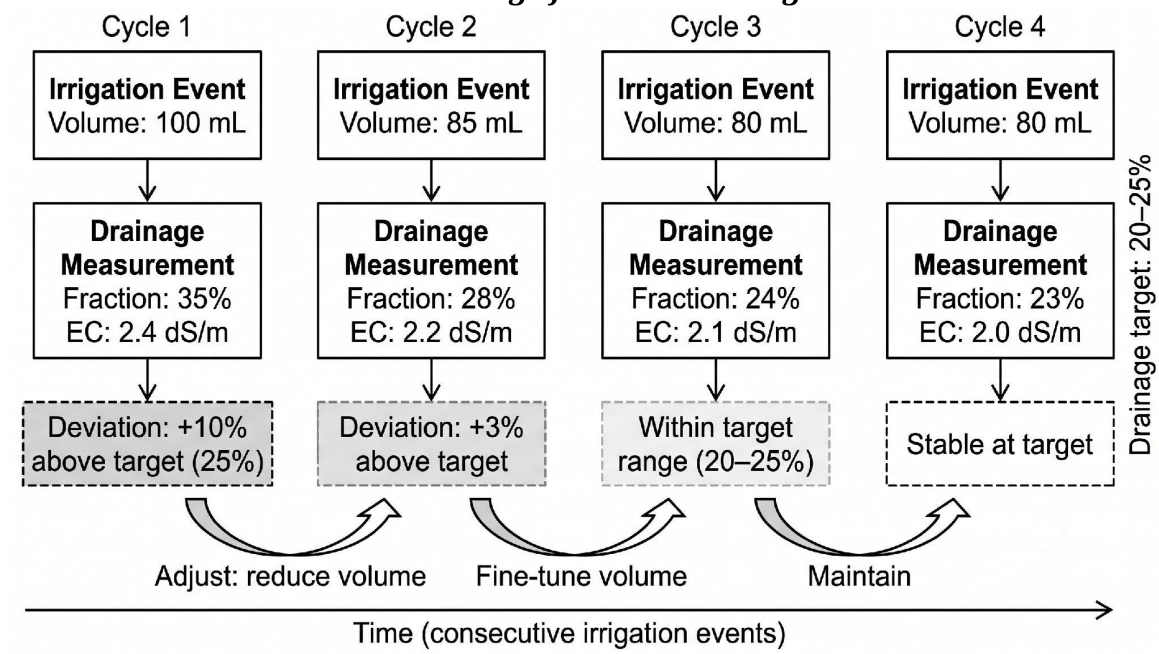

Figure 2. Drainage feedback temporal sequence: iterative volume adjustment across four consecutive irrigation cycles

Source: compiled by the author

Figure 2 illustrates the drainage feedback mechanism over four consecutive irrigation cycles. In Cycle 1, an initial irrigation volume of 100 mL produced a drainage fraction of 35 percent, exceeding the 25 percent target by 10 percentage points. Drainage EC registered 2.4 dS/m. Following the two-consecutive-event rule, the system reduced irrigation volume by 10 percent for Cycle 2 (85 mL), which brought drainage fraction to 28 percent and EC to 2.2 dS/m. A further reduction to 80 mL in Cycle 3 placed drainage fraction at 24 percent, within the target range of 20 to 25 percent. Cycle 4 maintained the 80 mL volume, and drainage fraction stabilized at 23 percent with EC at 2.0 dS/m.

Convergence to the target range required three adjustment cycles under stable environmental conditions. When external conditions shifted abruptly, for example during a transition from overcast to clear weather that increased transpiration and reduced drainage fraction below the target floor, the system responded by increasing volume in the subsequent cycle. Re-convergence after such perturbations typically required two to three additional cycles. Over the course of a full generative-mode period, the drainage feedback mechanism maintained drainage fraction within 5 percentage points of the target for over 80 percent of irrigation events, with deviations concentrated in the first two events following environmental transitions or mode switches.

ISSN: 2787-9364

Discussion

The resource savings reported in Section 4 result from three mechanisms operating simultaneously. Night irrigation elimination, a direct consequence of the PAR-based conjunctive trigger, removed one to two irrigation events per 24-hour cycle that the timer-based system delivered during hours of zero transpirational demand. During overcast conditions, reduced PAR accumulation slowed event triggering, cutting daily water input by approximately half compared with sunny days; under timer-based management, both day types received identical volumes. Through iterative volume adjustment, drainage fraction control tightened the per-event water dose to match the substrate's retention capacity, reducing the excess volume that would otherwise exit the system as leachate. Each mechanism addresses a distinct source of inefficiency: night elimination removes demand-independent events, cloudy-day adaptation scales input to actual energy conditions, and drainage control minimizes per-event excess. Operational records indicate that total savings remained stable across successive production cycles, suggesting sustained returns from the coordinated approach. Whether the three mechanisms contribute additively, synergistically, or with partial redundancy cannot be determined from the available data, as they were not tested independently.

Gallardo et al. [7] report water savings of 15 to 25 percent from model-assisted irrigation scheduling in Mediterranean greenhouses, where crop evapotranspiration estimates replaced fixed timers. SFM achieved approximately twice that reduction under different climatic and crop conditions. Direct comparison is limited by these contextual differences, but the magnitude of SFM's savings substantially exceeds the range reported for single-parameter model-assisted scheduling, consistent with the additional coordination complexity. Massa et al. [4] reduced drainage volume and nitrate emission in a semi-closed tomato system by managing recirculation thresholds; SFM achieves a comparable drainage-fraction outcome (20 to 25 percent) in an open-drain configuration without recirculation infrastructure, relying instead on precision volume control to limit excess at the emitter level.

Controlled drainage under SFM contributed to extended substrate operational lifespan. By limiting salt accumulation in the root zone through targeted leaching events and maintaining consistent air-water balance, SFM reduced the rate at which coconut coir degraded structurally and chemically over successive production cycles. Substrate replacement represents a significant operational cost in commercial greenhouse production; avoiding or delaying replacement improves the economic case for adaptive irrigation beyond the direct water and fertilizer savings captured in Table 1.

Seasonal mode switching emerged as a practically significant feature. Static irrigation parameters that optimize vegetative establishment may over-irrigate during fruiting and under-irrigate during late harvest, when root-zone conditions shift with canopy aging and declining radiation. SFM's three-mode structure accommodates these shifts by pre-configuring parameter sets aligned with each growth stage. Mode transitions in the current implementation are initiated manually by the production manager; this introduces a human judgment component that may delay or mistime the switch. Automating mode transitions based on measurable indicators of growth-stage change (cumulative degree-days, fruit set count, canopy cover fraction) would reduce dependence on subjective assessment and is a development priority for subsequent iterations of the system.

Operational scale provides a practical validation dimension. SFM managed irrigation across approximately 10 hectares of greenhouse strawberry production, demonstrating that the decision logic operates effectively at zone level without requiring per-plant granularity. Sensor placement followed standard commercial practice (representative slabs per zone), and the coordination rules processed zone-average data. Scaling to larger or more heterogeneous facilities would require evaluating whether zone-level averaging introduces meaningful spatial

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error, a question that can be addressed by comparing within-zone sensor variance across facilities of different size and configuration.

Limitations

Several constraints limit the generalizability of the reported results. First, the study presents a before-after comparison within a single facility, not a concurrent randomized trial. Environmental conditions (greenhouse climate, seasonal radiation patterns, cultivar selection) were comparable between the timer-based and SFM periods but were not experimentally matched. Confounding variables, including operator learning effects, substrate batch variation, and year-to-year weather differences, cannot be fully excluded. Second, all data originate from one crop (strawberry), one substrate (coconut coir), and one climatic context (temperate continental, Kyiv Oblast). Transferability to other crop-substrate combinations, climatic zones, or greenhouse configurations cannot be assumed without independent validation.

Third, yield was recorded as total marketable fruit weight per plant; fruit quality parameters (soluble solids, firmness, shelf life) were not systematically measured and may have been affected by the irrigation regime in ways not captured by weight alone. Fourth, seasonal mode transitions were initiated manually; the timing of each switch depended on the production manager's assessment of growth stage, introducing a source of variability that would not be present in a fully automated system. Fifth, no independent replication of SFM has been conducted at another facility. Sixth, the baseline timer-based system may not represent best-practice timer management; operations with more carefully calibrated timer schedules might show a smaller differential relative to SFM. All reported savings should be interpreted as specific to the conditions described and not as universally achievable benchmarks.

Author's Contribution

The author developed the Smart-Flow Matrix (SFM), an adaptive irrigation management framework for commercial hydroponic greenhouse production. Original contributions include: the five-stream data integration architecture combining feed-forward anticipation with feedback verification; the conjunctive dual-threshold irrigation logic; the EC trajectory correction mechanism based on a three-day rolling average; the drainage feedback convergence algorithm with iterative volume adjustment; and the seasonal mode-switching model with three growth-stage-specific parameter sets (vegetative, generative, late harvest). Operational deployment at greenhouse scale (approximately 10 hectares) and the resource-efficiency and yield metrics reported in Section 4 are original results from the author's production management practice.

Conclusions

Smart-Flow Matrix was described as an adaptive irrigation management framework combining feed-forward anticipation with feedback verification and seasonal mode switching across vegetative, generative, and late harvest growth stages. Comparison of operational records from the SFM deployment period with the preceding timer-based baseline in the same facility indicated a reduction of approximately 45 to 50 percent in water and fertilizer consumption. Three mechanisms contributed to this outcome: elimination of demand-independent night irrigation, proportional reduction of water input on low-radiation days, and per-event volume control through drainage feedback.

Yield reached 1.7 to 1.87 kilograms per plant under commercial conditions, and yield stability was maintained through all seasonal mode transitions. Drainage fraction converged to target ranges within three to four irrigation cycles following parameter adjustments and remained within 5 percentage points of the target for over 80 percent of events during the generative period.

Directions for further research include: (a) controlled concurrent trials comparing SFM against calibrated single-parameter and dual-parameter irrigation systems under identical conditions; (b) validation across additional crops, substrates, and climatic regions; (c)

ISSN: 2787-9364

integration of automated growth-stage detection to replace manual mode switching; and (d) systematic measurement of fruit quality parameters to assess whether the irrigation regime affects post-harvest attributes beyond yield weight.

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